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An experimental investigation of bilateral oligopoly in emissions trading markets

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ABSTRACT

Market power in emissions trading has been extensively investigated because emerging markets for tradable emissions permits, such as the European Union's Emissions Trading Scheme (ETS), can be dominated by relatively few large sellers or buyers. Previous studies on market power in emissions trading have assumed the existence of a subset of competitive players. However, a key feature of emissions trading markets is that emissions permits are often traded by a small number of large sellers and buyers. Using a laboratory experiment, our objective in this paper is to test the performance of an emissions trading market utilizing a double auction in a bilateral oligopoly. Our results suggest that the theoretical bilateral oligopoly models can better describe market outcomes of emissions trading. The effects of the slope of the marginal abatement cost function on market power in laboratory experiments are found to be consistent with those predicted by the theoretical bilateral oligopoly model. How market power is exercised depends on the curvature of the abatement cost function. If the marginal abatement cost function of buyers (sellers) is less steep than that of sellers (buyers), the price of permits is lower (higher) than that under perfect competition. This is because the market power of buyers (sellers) exceeds that of sellers (buyers). The price of permits is close to the perfect competitive price when all traders have the sameslope of the marginal abatement cost function.

1. Introduction

Market power in emissions trading has been extensively investigated because emerging markets for tradable emissions permits, such as the European Union's Emissions Trading Scheme (EU-ETS), can be dominated by relatively few large sellers or buyers. Haita (2014) noted that the number of bidders for the spot auction of the EU-ETS was never larger than 20 during the first half of 2013. Additionally, tradable permit schemes have been applied to address local environmental problems, such as water quality trade. In such schemes, the number of permit traders is limited because only a few players can join such localized markets. Previous studies have analyzed market power in the case of actual small markets (Doyle, Patterson, Chen, Schnier, & Yates, 2014; Yates, Doyle, Rigby, & Schnier, 2013). Based on this background, reducing market power in permit trading is an important policy issue.

Previous studies on market power in emissions trading assume the existence of a subset of competitive players. However, a key feature of emissions trading markets is that emissions permits are often traded by a small number of large sellers and buyers. Thus,

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both sellers and buyers can influence the market price in their favor, and emissions trading markets can be considered a bilateral oligopoly where every trader can exercise market power.[1]

Using a laboratory experiment, our objective in this paper is to test the performance of an emissions trading market utilizing a double auction in a bilateral oligopoly. The issue we address is the robustness of how a double auction mitigates market power in emissions trading. Until now, many researchers have empirically analyzed market power in a double auction market (Smith, 1981; Smith & Williams, 1990), and the adverse impact of market power has been an important issue for theoretical analyses of permit trading (Hahn, 1984).

Prior to emissions trading, the administrator is required to determine the initial endowment of permits, which may exacerbate the adverse impact of market power on efficiency. However, the literature on laboratory experiments of double auctions indicates that a double auction could achieve an efficient outcome even if dominant traders exert market power. If that is the case, the administrator should apply a double auction to emissions trading. To investigate how a double auction affects market power in emissions trading, Godby (1999) conducted a laboratory experiment that assumed an imperfectly competitive market, such as a monopoly or duopoly, with a double auction. He found that the efficiency gain was not significantly different between duopoly, monopoly and competitive markets. Furthermore, Ledyard & Szakaly-Moore, 1994compared the market outcome between a double auction and a revenue neutral auction in a laboratory experiment of emissions trading. They revealed that a double auction could reduce market power more than a revenue neutral auction. Furthermore, Cason, Gangadharan, and Duke (2003) showed that compared with a perfectly competitive market, a monopoly market does not cause any efficiency loss if a double auction is applied to emissions trading. These studies showed that double auctions can curb market power under imperfect competition.

Although the literature on laboratory experiments of emissions trading reveals the effectiveness of double auctions, it focuses on traditional models of imperfect competition, which assume market power either on the sellers' side or on the buyers' side. In fact, some studies have noted that a double auction may not achieve an efficient outcome if the market in question cannot be well described by a traditional model of imperfect competition (Muller, Mestelman, Spraggon, & Godby, 2002; Sturm, 2008). Thus, the important research question is whether a double auction curbs market power in emissions trading where both sellers and buyers can exert market power.

In contrast to the experimental literature on market power, the benchmark for the experiment in our study is derived from theoretical bilateral oligopoly models for emissions trading, including a share auction (SA) model, a noncompetitive equilibrium (NCE) model, and a supply function equilibrium (SFE) model. The SA model was developed by Wirl, 2009, Section 6, who applied the uniform price auction for multiple units in Wilson (1979) to emissions trading. The NCE model was developed by Lange (2012), who applied the slope-taking equilibrium of Weretka (2011) to emissions trading. The SFE model was developed by Malueg and Yates (2009), who applied the supply function equilibrium models of Klemperer and Meyer (1989) and of Hendricks and McAfee (2010) to emissions trading. These models have the potential to better describe the real behavior of emissions trading because previous studies of laboratory experiments that analyzed the imperfect competitive situation of emissions trading have already shown that the traditional model cannot explain market outcomes well. Almost all laboratory experiments of tradable permits consist of a limited number of sellers and buyers. Therefore, the model of bilateral oligopoly is more suitable for the analysis of market power in the laboratory experiment of tradable permits.

Although theoretical models that focus on bilateral oligopoly have already been developed in the literature, there is little empirical analysis of the extent to which these models can predict actual trading in the permit market. Schnier, Doyle, Rigby, and Yates (2014) investigated whether a SFE model can predict permit trading in a laboratory experiment. They focused only on the SFE model in their analysis of bilateral oligopoly and did not employ a double auction. In contrast, this study treats alternative models of bilateral oligopoly in emissions trading markets, such as SFE, SA and NCE models, and applies a double auction to emissions trading. The model of bilateral oligopoly can also apply to understand the energy related market. Therefore, it is the crucial researcher that we test the model how much well describe actual trading behavior.

Section 2 presents theoretical bilateral oligopoly models in an emissions trading market, and it summarizes the research questions addressed in the laboratory experiment. Section 3 describes the experimental design and theoretical predictions of alternative bilateral oligopoly models. Section 4 presents the results of the experiment, and Section 5 concludes the analysis. The appendix presents the model derivation, proof of propositions, and additional results of the experiment. It also demonstrates that the demand functions for permits in the NCE model coincide with those in the linear demand function equilibrium model of Wirl, 2009, Section 5.

2. Theoretical models

2.1. Related literature

In the bilateral oligopoly models, every trader can exercise market power, which is determined endogenously as part of the equilibrium process. The ability of each trader to influence the prices of emissions permits depends on his or her production technology as well as the size and number of traders in the market. Consequently, SA, NCE and SFE models are less restrictive than traditional imperfect competition models applied in the experimental literature, such as monopoly, monopsony, and Cournot models, which a priori assume that a seller or buyer may have dominating market power. As the number of traders increases, market

[1] Hintermann (2017) provided the empirical evidence for price manipulation by the ten largest electricity firms during phase I of the EU-ETS and suggested that market power is likely to be an empirically relevant concern during the early years of emission permit markets.

outcomes predicted by bilateral oligopoly models converge to those in perfect competition.

There are some notable differences among bilateral oligopoly models with regard to the assumption about the behavior of buyers and sellers in emissions trading. The SA model assumes that a trader's strategy is a bid function that defines a residual supply function for each trader in a Bayesian-Nash game. In the SA model, the equilibrium price is determined by the intersection of the residual supply function with the bid function. The NCE model assumes that the equilibrium results from endowing all traders with consistent beliefs about the slopes of the market's supply and demand curves. It also assumes that each trader chooses quantity to maximize its profit in the emissions trading market. The SFE model assumes that each trader selects a supply function from a one-parameter family of nonlinear schedules indexed by its capacity for production or consumption. It also assumes that each trader reports the supply function to auctioneers.

2.2. Defining the emissions trading market

We consider an emissions trading market where all firms with an initial endowment of emissions allowances can affect the price of permits, denoted by p. Prior to emissions trading, firms have made production commitments so that both the product price and product quantity are fixed. Given the initial endowment of allowances and abatement technology, firms trade emissions permits at a uniform price for each independent time period. No permit banking is allowed.

Following Wirl (2009), we assume that an emissions trading market consists of n_b buyers and n_s sellers. Because our focus is on bilateral oligopoly, the number of firms, $n_b + n_s$, is assumed to exceed two for the rest of the paper. In addition, the number of buyers is assumed to be equal to that of sellers: $n_b = n_s = n$. Buyers are symmetric in that their marginal abatement cost functions are identical and they have the same initial endowment of permits. Similarly, sellers are symmetric; they have identical marginal abatement cost functions and the same initial allocation of permits. Without any effort in abatement, every firm emits x.[2] The abatement level for buyer i, denoted by a_i, is given by

$$a_i = x - z_b - y_i,$$

and the abatement level for seller j, denoted by a_j, is given by

$$a_j = x - z_s - \psi_j,$$

where z_b and z_s denote the initial endowment of permits for buyers and sellers, respectively, and y_i and ψ_j denote the net trade of permits for buyer i and seller j, respectively. It is assumed that $y_i \geq 0$ and $\psi_j \leq 0$. The abatement cost function for buyer i is denoted by $k(a_i)$, and that for seller j is denoted by $\kappa(a_j)$. These functions are assumed to be quadratic and take the following form:

$$k(a_i) = c_0 a_i + 0.5 c a_i^2 \tag{1}$$

$$\kappa(a_j) = \gamma_0 a_j + 0.5 \gamma a_j^2 \tag{2}$$

where c, c_0, γ, and γ_0 denote parameters. Note that Wirl (2009) assumes $c_0 = \gamma_0 = 0$ and Malueg and Yates (2009) assume $c = \gamma$ in their analysis of bilateral oligopoly in an emissions trading market.

2.3. The SA model

Following Wirl, 2009, Section 6, in the SA model, we assume that buyer i determines y_i given the price function of all other buyers, denoted by a vector $[P1, P2, \ldots, p_h \neq i, \ldots, Pn]$, and the price function of all sellers, denoted by a vector $[\Pi_1, \Pi_2, \ldots, \Pi_n]$. Similarly, seller j is assumed to determine ψ_j given price vectors $[P1, P2, \ldots, Pn]$ and $[\Pi_1, \Pi_2, \ldots, \Pi_{h \neq j}, \ldots, \Pi_n]$. These price functions for each buyer and seller are assumed to be linear in parameters and take the following forms:

$$P(y_i) = P_0 - q y_i \quad , P_0 > 0, q > 0 \tag{3}$$

$$\prod (\psi_j) = \Pi_0 - \eta \psi_j \quad , \Pi_0 > 0, \eta > 0 \tag{4}$$

where q, η, P_0, and Π_0 denote parameters. Since all buyers are symmetric, $y_i = y_t = y$, $i \neq t$. Similarly, because of symmetry in sellers, $\psi_j = \psi_h = \psi$, $j \neq h$. Thus, at equilibrium, the market clears and the following condition for market clearing holds:

$$n(\psi + y) = 0$$

This implies that the buyers' and sellers' price functions can be described by

$$P\left[-\frac{\psi_j + (n-1)\psi}{n}\right] \tag{5}$$

and

[2] We focus on how abatement technology and initial endowments of permits affect emissions trading given x, emissions without any effort, which are determined by firms' production levels. By assuming no difference in x across firms, we attempt to exclude the effect of firm size (production level) on emissions trading.

$$\Pi\left[-\frac{y_i+(n-1)y}{n}\right]. \tag{6}$$

From (5) and (6), the objective function of buyer i and that of seller j are written as

$$\max_{y_i} - k(x - z_b - y_i) - y_i \Pi\left[-\frac{y_i+(n-1)y}{n}\right] \tag{7}$$

and

$$\max_{\psi_j} - \kappa(x - z_s - \psi_j) - \psi_j P\left[-\frac{\psi_j+(n-1)\psi}{n}\right]. \tag{8}$$

Inserting a boundary condition that the price at zero trading is equal to the marginal abatement cost into the price functions in (3) and (4) leads to

$$P(y_i) = c_0 + c(x - z_b) - qy_i \tag{9}$$

and

$$\prod(\psi_j) = \gamma_0 + \gamma(x - z_s) - \eta\psi_j. \tag{10}$$

The first-order conditions of (7) and (8) along with the market clearing condition yield the optimal quantity of permit trade:

$$y^A = \frac{n[(c-\gamma)x - (cz_b - \gamma z_s) + (c_0 - \gamma_0)]}{\eta(n+1) + nc} \tag{11}$$

$$\psi^A = -\frac{n[(c-\gamma)x - (cz_b - \gamma z_s) + (c_0 - \gamma_0)]}{q(n+1) + n\gamma} \tag{12}$$

where y^A and ψ^A denote the optimal trade for each buyer and that for each seller, respectively, and parameters η and q can be rewritten as

$$\eta = \frac{n(c + n\gamma)}{n^2 - 1} \tag{13}$$

$$q = \frac{n(nc + \gamma)}{n^2 - 1}. \tag{14}$$

The equilibrium price, denoted by p^A, is given by

$$p^A = \frac{(c + n\gamma)[c_0 + c(x - z_b)] + (nc + \gamma)[\gamma_0 + \gamma(x - z_s)]}{(n+1)(c+\gamma)} \tag{15}$$

At equilibrium, the markup for each buyer is given by $-\eta y^A/n$, while that for each seller is given by.
$-q\psi^A/n$. The optimal trade is given by

$$y^A = \left[\frac{n-1}{n(c+\gamma)}\right](\gamma z_s - cz_b + c_0 - \gamma_0) \tag{16}$$

and

$$\psi^A = -\left[\frac{n-1}{n(c+\gamma)}\right](\gamma z_s - cz_b + c_0 - \gamma_0). \tag{17}$$

Appendix A.1 presents the derivation of Eqs. (15), (16), and (17). Note that if all firms share an identical slope of the marginal abatement cost function, i.e., $c = \gamma$, then the permit price at an NCE is equal to that at competitive equilibrium. In this case, $p^A = \mu_0 + \beta(x - z_a)$, where $\mu_0 \equiv 0.5(c_0 + \gamma_0)$, $Z_a \equiv 0.5(z_b + z_s)$, and $\beta = c = \gamma$.

2.4. The NCE model

An NCE of the emissions trading market is defined as triple the permit price, net sales of permits, and price impacts such that (i) the 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 (Lange, 2012; Weretka, 2011). Buyer i's ability to affect the price is represented by the price impact, which is defined as $\partial p/\partial y_i$. Similarly, the price impact associated with seller j is $\partial p/\partial \psi_j$. Market clearing and optimization are also assumed in the models of perfect and imperfect competition. What makes the NCE model 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. Models of imperfect competition, such as the Cournot model, assume that when one strategic firm deviates from equilibrium by changing its net sales of permits, other strategic firms hold their net sales of permits constant. In these models, competitive fringe absorbs any deviation from equilibrium.

Given the response to the market price by other firms, buyer i and seller j determine their net sales of permits to maximize their profit subject to the abatement technology:

$$\max_{p} - k(x - z_b - y_i) - py_i \tag{18}$$

$$\max_{p} - \kappa(x - z_s - \psi_j) - p\psi_j \tag{19}$$

Under symmetry, the first-order conditions for profit maximization in (18) and (19) yield the following demand functions for permits:

$$y^N = f^N(p) = -\frac{m_b[p - c_0 - c(x - z_b)]}{1 + cm_b} \tag{20}$$

$$\psi^N = \varphi^N(p) = -\frac{m_s[p - \gamma_0 - \gamma(x - z_s)]}{1 + \gamma m_s} \tag{21}$$

where $m_b \equiv \partial y_i/\partial p$ and $m_s \equiv \partial \psi_j/\partial p$. From (20) and (21), the markup for buyer i and that for seller j can be written as $-\theta_b y_i$ and $-\theta_s \psi_j$, respectively, where $\theta_b \equiv 1/m_b$ and $\theta_s \equiv 1/m_s$. The larger θ_b or θ_s becomes, the more market power buyer i or seller j exerts. Note that in the case of competitive equilibrium, each firm has no price impact. Thus, θ_b and θ_s are zero, and the permit price is equal to the marginal abatement cost at competitive equilibrium.

In the NCE model, each firm is assumed to change its net sales of permits by a sufficiently small amount so that it can obtain a good estimate of the price impact of other firms. 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 each firm. The slope of the inverse demand function is given by the estimates of θ_b and θ_s. As a result of these responses, the market clears and the permit price returns to the equilibrium level. Specifically, the price impacts are estimated numerically by solving the system of the following equations:

$$m_b + \frac{m_b}{1 + cm_b} = \frac{n(m_b + m_s)}{2n - 1} \tag{22}$$

$$m_s + \frac{m_s}{1 + \gamma m_s} = \frac{n(m_b + m_s)}{2n - 1} \tag{23}$$

Eqs. (22) and (23) imply that the smaller c or γ is, the larger θ_b or θ_s. Thus, the price impacts of firms depend on the convexity of firms' cost functions.

The equilibrium price of permits in the NCE model, p^N, is obtained by solving the condition for market clearing:

$$p^N = \frac{M_b(cx + c_0) + M_s(\gamma x + \gamma_0) - M_b c z_b - M_s \gamma z_s}{M_b + M_s} \tag{24}$$

where $M_b \equiv m_b/(1 + cm_b)$ and $M_s \equiv m_s/(1 + \gamma m_s)$. The optimal trade of each firm is given by

$$y^N = \left(\frac{M_b M_s}{M_b + M_s}\right)[c_0 - \gamma_0 + c(x - z_b) - \gamma(x - z_s)] \tag{25}$$

and

$$\psi^N = -\left(\frac{M_b M_s}{M_b + M_s}\right)[c_0 - \gamma_0 + c(x - z_b) - \gamma(x - z_s)]. \tag{26}$$

Note that if all firms share an identical slope of the marginal abatement cost function, i.e., $c = \gamma$, then the permit price at an NCE is equal to that at competitive equilibrium. In this case, from (22) and (23), $m_b = m_s = 2(n - 1)/\beta$, where $\beta = c = \gamma$.

2.5. The SFE model

Following Malueg & Yates, 2009, Section 3, we assume that each firm has an identical slope of the marginal abatement cost function, i.e., $c = \gamma$, because it is not possible to obtain an explicit solution for the case of varied slopes across n firms in the SFE model. The intercepts of the marginal abatement cost functions are assumed to be common knowledge to all firms. Each firm is assumed to strategically report its demand function of permits to the market maker to maximize profits. Then, the demand function for permits can be written as

$$y_i = f^S(p) = -\frac{p - c_{0i} - \beta(x - z_b)}{\beta} \tag{27}$$

for buyer i and

$$\psi_j = \varphi^S(p) = -\frac{p - \gamma_{0j} - \beta(x - z_s)}{\beta} \tag{28}$$

for seller j, respectively, where $\beta = c = \gamma$, and c_{0i} and γ_{0j} are parameters buyer i and seller j report to the market maker. If $c_{0i} = c_0$ and $\gamma_{0j} = \gamma_0$, the optimal trade of permits is equal to that at competitive equilibrium.

Given other firms' reports on their demand functions, the objective function is

$$\max_{c_{0i}} - k(x - z_b - f^S(p)) - pf^S(p) \tag{29}$$

for buyer i and

$$\max_{\gamma_{0j}} - \kappa(x - z_s - \varphi^S(p)) - p\varphi^S(p) \tag{30}$$

for seller j. Under symmetry, the first-order condition for (29) is given by

$$c_{0b} = c_0 + \left(\frac{1}{2n}\right)[(\mu_0 - \beta z_a) - (c_0 - \beta z_b)] \tag{31}$$

for each buyer and that for (30) is given by

$$\gamma_{0s} = \gamma_0 + \left(\frac{1}{2n}\right)[(\mu_0 - \beta z_a) - (\gamma_0 - \beta z_s)] \tag{32}$$

for each seller, where symmetry implies that $c_{0i} = c_{0t} = c_{0b}$, $i \neq t$ and that $\gamma_{0j} = \gamma_{0h} = \gamma_{0s}$, $j \neq h$. The market clearing condition yields the price of permits at equilibrium in the SFE model, p^S:

$$p^S = \mu_0 + \beta(x - z_a) \tag{33}$$

The optimal trade of each firm is given by

$$y^S = \left(\frac{2n-1}{2n\beta}\right)[(c_0 - \beta z_b) - (\mu_0 - \beta z_a)] \tag{34}$$

$$\psi^S = -\left(\frac{2n-1}{2n\beta}\right)[(\gamma_0 - \beta z_s) - (\mu_0 - \beta z_a)]. \tag{35}$$

Eq. (33) indicates that the equilibrium price of permits in the SFE model is equal to that under perfect competition. The markup for each buyer is

$$p^S - k' = c_{0b} - c_0 = \left(\frac{1}{2n}\right)[(\mu_0 - \beta z_a) - (c_0 - \beta z_b)], \tag{36}$$

and the markup for each seller is

$$p^S - \kappa' = \gamma_{0s} - \gamma_0 = \left(\frac{1}{2n}\right)[(\mu_0 - \beta z_a) - (\gamma_0 - \beta z_s)] \tag{37}$$

where k' and κ' denote the marginal abatement cost for buyers and sellers, respectively.

Notably, Wirl, 2009, Section 5 also applies an SFE model to the analysis of bilateral oligopoly in emissions markets and develops the model of "linear demand function equilibrium" (LDFE). As Appendix A.2 demonstrates, the linear demand function for permits in the model by Wirl, 2009, Section 5 coincides with that in the NCE model. Thus, in our study, we do not consider the LDFE model. Throughout the analysis, the number of buyers is assumed to be equal to that of the sellers. As a reference, Appendix A.3 summarizes the comparison of the equilibrium quantity of trade across three models of bilateral oligopoly for the case that $c = \gamma$ and the number of buyers is different from that of the sellers.

2.6. Research questions

The models presented above raise important research questions that we address using laboratory experiments. First, the effect of each firm's trade on the market price of permits depends on the curvature of the abatement cost function in both the SA and NCE models of bilateral oligopoly. The following proposition indicates how the slope of the marginal abatement cost function affects the markup that indicates the market power of each firm.[3]

Proposition 1. *In the case of n identical sellers and n* identical buyers trading emissions permits under bilateral oligopoly described by either the SA or NCE model,

[3] The effect of marginal abatement cost functions on emissions trading has been investigated previously in studies that examine how the differences in the slope of marginal abatement cost functions affect market outcomes. See Ellerman, Joskow, Schmalensee, Bailey, and Montero (2000) for the effects of marginal abatement cost functions in the US acid rain program.

$|p - k'| > |p - \kappa'|$ if $c < \gamma$,
$|p - k'| = |p - \kappa'|$ if $c = \gamma$, and.
$|p - k'| < |p - \kappa'|$ if $c > \gamma$,
where $|p - k'|$ and $|p - \kappa'|$ denote the absolute value of $p - k'$ and that of $p - \kappa'$, respectively.
*Proof S*ee Appendix A.4.

In the SA model, the effect of trade on the market price is given by

$$\frac{\partial}{\partial y_i}\Pi\left[-\frac{y_i + (n-1)y}{n}\right]$$

for buyer i and

$$\frac{\partial}{\partial \psi_j}P\left[-\frac{\psi_j + (n-1)\psi}{n}\right]$$

for seller j. Thus, the effect of trade on the price is η/n for each buyer and q/n for each seller. From (13) and (14), the difference in this effect between buyers and sellers is $(\gamma - c)/(n+1)$, which indicates that if the slope of the marginal abatement cost function of each permit seller is smaller (larger) than that of each buyer, the effect of trade on the price for each seller is larger (smaller) than that for each buyer. Turning to the NCE model, from (22) and (23), the smaller c or γ is, the larger θ_b or θ_s. Thus, in the NCE model, if the slope of the marginal abatement cost function of each permit seller is smaller (larger) than that of each buyer, the effect of trade on the price for each seller is larger (smaller) than that for each buyer. Note that Proposition 1 holds in the SFE model because the absolute value of the markup is identical across all firms assuming $c = \gamma$.

Second, the effects of the initial endowment of emissions allowances also depend on the curvature of the abatement cost function in both the SA and NCE models of bilateral oligopoly. The following proposition summarizes the effects of the initial allocation of emissions permits on the market price:

Proposition 2. *In the case of n identical sellers and n* identical buyers trading emissions permits under bilateral oligopoly that is described by either the SA or NCE model,
$\frac{\partial p}{\partial z_b}\ |Z\ is\ given > 0, \frac{\partial p}{\partial z_s}\ |Z\ is\ given < 0$ if $\gamma > c$,
$\frac{\partial p}{\partial z_b}\ |Z\ is\ given = 0, \frac{\partial p}{\partial z_s}\ |Z\ is\ given = 0$ if $\gamma = c$, and.
$\frac{\partial p}{\partial z_b}\ |Z\ is\ given < 0, \frac{\partial p}{\partial z_s}\ |Z\ is\ given > 0$ if $\gamma < c$,
where Z denotes the total number of permits.
Proof See Appendix A.5.

Given the total quantity of emissions permits, if the market power of buyers exceeds that of sellers (i.e., $\gamma > c$), an increase in the initial allocation of sellers' permits strengthens the market power of buyers, thereby lowering the market price (i.e., $\frac{\partial p}{\partial z_s}\ |Z\ is\ given < 0$). In contrast, the market price is raised by an increase in the initial allocation of sellers' permits (i.e., $\frac{\partial p}{\partial z_s}\ |Z\ is\ given > 0$) if the market power of sellers exceeds that of buyers (i.e., $\gamma < c$). If all firms share an identical slope of the marginal abatement cost function, as in the SFE model, the initial allocation of permits has no effect on the market price.

Finally, if all firms share an identical slope of the marginal abatement cost function, the permit price at the equilibrium of the SA, NCE or SFE model of bilateral oligopoly is equal to that at competitive equilibrium. This holds for any feasible allocation of permits prior to trading and is summarized by the following proposition:

Proposition 3. The price of permits at the equilibrium of bilateral oligopoly coincides with that at competitive equilibrium if all firms share an identical slope of the marginal abatement cost function.
*Proof S*ee Appendix A.6.

3. Experimental design

We conducted a computerized laboratory experiment at Tohoku University in March 2011 and March 2013 using the "z-Tree" program (Fischbacher, 2007). The experiment included eight sessions, each lasting approximately 90 min. Thirty-two subjects were randomly assigned to each session. In each session, four subjects traded emissions permits in a computerized single-unit double auction.

The DA is a real-time trading institution in which agents can submit bids to buy and offers to sell permits; the agents can accept the best bid or offer made by other agents at any time during a trading period of several minutes (Davis & Holt, 1993). Many previous studies have already shown that the double auction institution consistently produces very efficient allocations and prices (Friedman, 1993; Smith, 1962). The institution is employed in several kinds of trading, such as financial assets including tradable permits. Therefore, many previous studies of laboratory experiments related to emissions trading have employed a double auction for trading permits. Our experiment uses a double auction to trade permits and for comparison with previous studies.

The number of trading periods was ten, and this number was disclosed to the subjects at only the end of the session. Many previous studies have set the number of periods to approximately ten (Cason et al., 2003; Muller et al., 2002). Following these studies, each session of our experiment consists of ten periods.[4] In each period, the subjects can trade permits between three minutes in a real-time double auction trading market. Most subjects were either undergraduate students or vocational school students. They did not know who participated in the session. Each subject participated in one of the eight sessions and received an average of US $30 (1 US dollar = 80 yen) as a reward, which depended on how much they earned by trading permits in the experiment. Prior to each session, we explained the trading rules to the subjects and asked them 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 ensured that the subjects fully understood the trading rules by holding a practice session before the experiment started.

Table 1 summarizes the experimental design. Holding the total emissions constant to 40, we initiated nine treatments that differed in the initial endowment of emissions permits and the marginal abatement cost functions. We conducted eight sessions for each treatment. For each treatment, we assumed the abatement cost functions in (1) and (2) and the initial allocation of emissions permits so that subjects A and B would be buyers and subjects C and D would be sellers. To determine the effect of the convexity of the abatement cost function on market power, parameter c for subjects A and B was assumed to be smaller than parameter γ for subjects C and D in Treatments 1, 2 and 3.[5] As indicated by Proposition 1, buyers' market power was expected to exceed that of sellers in these treatments given the initial allocation of emissions permits. In contrast, sellers' market power was expected to exceed that of buyers in Treatments 4, 5 and 6 because parameter γ for subjects C and D was assumed to be smaller than parameter c for subjects A and B in Treatments 4, 5 and 6. In Treatment 7, all subjects had an identical slope of the marginal abatement cost function and the same number of emissions permits. In Treatments 8 and 9, all subjects had the same parameter γ, but the initial allocation of emissions permits differed between sellers and buyers. The price of permits was expected to be equal to the competitive price in Treatments 7, 8 and 9, as indicated by Proposition 3. To demonstrate the effect of the initial allocation of emissions permits on the price of permits, as indicated by Proposition 2, the initial allocation of emissions permits differed across subjects in Treatments 2, 3, 5, 6, 8 and 9, while the same number of permits was initially assigned to each subject in Treatments 1, 4 and 7.

Table 2 summarizes the theoretical predictions of the alternative bilateral oligopoly models. For each treatment, the equilibrium price of emissions permits was 130 at competitive equilibrium (see Table 2.D), and the competitive distribution of emissions placed 20 with subjects A and B and 0 with subjects C and D. In Table 2, the absolute value of the Lerner index, $|(p - k')/p|$ for a buyer and $|(p - \kappa')/p|$ for a seller, is used to measure each trader's market power. These values indicate how much each trader can deviate the price from the marginal abatement cost by exercising market power. Since the market power of buyers is assumed to exceed that of sellers in Treatments 1, 2 and 3, the price of permits under the bilateral oligopoly is lower than that under perfect competition, and the profits of buyers (sellers) under the bilateral oligopoly are larger (smaller) than those under perfect competition. In contrast, the price of permits under the bilateral oligopoly is higher than that under perfect competition, and the profits of sellers (buyers) under the bilateral oligopoly are larger (smaller) than those under perfect competition in Treatments 4, 5 and 6. In Treatments 7, 8 and 9, the price of permits under the bilateral oligopoly is equal to the competitive price, but the profits of all traders under the bilateral oligopoly are lower than those at competitive equilibrium. Under the bilateral oligopoly, the effect of the initial allocation of permits on the market price indicates that the price of permits in Treatment 2 is lower than that in Treatment 1. This effect also indicates that the price of permits in Treatment 5 is higher than that in Treatment 4 under the bilateral oligopoly.

To determine the loss in allocative efficiency due to market power, we compute an efficiency measure of the bilateral oligopoly relative to competitive equilibrium, which is defined as the ratio of an increase in aggregate profits due to emissions trading under the bilateral oligopoly to that under competitive equilibrium (Ledyard & Szakaly-Moore, 1994). In all treatments, the market power of the bilateral oligopoly reduced efficiency because it discouraged the trade of permits in the market. In all bilateral oligopoly models, the total volume of permits traded is smaller than that under perfect competition. This reduction in trade leads to a loss in allocative efficiency, which ranges from 7.5% to 25%. For all treatments, efficiency loss in the SA model exceeds that in the NCE model. This is consistent with the result in Wirl (2009), who compared efficiency between the SA and LDFE models.

4. Results

4.1. Price of permits

We compare the price of emissions permits across all treatments. Fig. 1 and Table 3 show the average permit price for each treatment. During all periods of the experiment, the observed prices of permits in Treatments 1, 2 and 3 were persistently lower than the competitive price of 130, and the observed prices of permits in Treatments 4, 5 and 6 were persistently higher than the competitive price. In Treatments 7, 8 and 9, the observed price of permits was close to that at competitive equilibrium in most of the trading periods. These observations are consistent with Hypotheses 1 and 3. Moreover, the price of permits in Treatment 2 was persistently lower than that in Treatment 1, while the price of permits in Treatment 5 exceeded that in Treatment 4. These findings

[4] In each session, each subject read the instruction of this experiment for approximately ten minutes. After they read the instruction, the experimenter explained how to do the trading and decision making in this experiment again. To familiarize the subjects with the experiments, we ran two training periods before the experiment.

[5] Total trade relative to the competitive equilibrium and efficiency relative to the competitive equilibrium do not change across all treatments in the SA model. When $n = 2$, the total trade for the SA model and that for competitive equilibrium are

$2y^A = \frac{\gamma z_s - c z_b + c_0 - \gamma_0}{c + \gamma}$ and $2y^* = \frac{2(c_0 - \gamma_0) + 2(\gamma z_s - c z_b)}{c + \gamma}$.

Since $c_0 - \gamma_0 = 20$ for all treatments in the experiment, $\frac{2y^A}{2y^*} = \frac{20 + \gamma z_s - c z_b}{2(20 + \gamma z_s - c z_b)} = 0.5$.

Table 1
Experimental setting.

Subject		A (buyer)	B (buyer)	C (seller)	D (seller)
Treatment 1	c, γ	1	1	5	5
	c_0, γ_0	150	150	130	130
	z_b, z_s	10	10	10	10
Treatment 2	c, γ	1	1	5	5
	c_0, γ_0	150	150	130	130
	z_b, z_s	6	6	14	14
Treatment 3	c, γ	1	1	5	5
	c_0, γ_0	150	150	130	130
	z_b, z_s	14	14	6	6
Treatment 4	c, γ	5	5	1	1
	c_0, γ_0	230	230	130	130
	z_b, z_s	10	10	10	10
Treatment 5	c, γ	5	5	1	1
	c_0, γ_0	230	230	130	130
	z_b, z_s	6	6	14	14
Treatment 6	c, γ	5	5	1	1
	c_0, γ_0	230	230	130	130
	z_b, z_s	14	14	6	6
Treatment 7	c, γ	1	1	1	1
	c_0, γ_0	150	150	130	130
	z_b, z_s	10	10	10	10
Treatment 8	c, γ	1	1	1	1
	c_0, γ_0	150	150	130	130
	z_b, z_s	6	6	14	14
Treatment 9	c, γ	1	1	1	1
	c_0, γ_0	150	150	130	130
	z_b, z_s	14	14	6	6

regarding the effects of the initial allocation of permits on the price are consistent with Proposition 2. The persistent difference in the market price of permits is statistically confirmed by the Mann-Whitney test with the null hypothesis that probability distributions of the price are identical across treatments. In previous studies, the closing price of a trade has been shown to be a better benchmark to compare each treatment (Kotani, Tanaka, & Managi, 2019). Therefore, we employ the closing price of each period as the sample of this test. We show the test result in Table 4. Nearly all test results show a consistent result with the theoretical perspective considering bilateral oligopoly. For example, the test results show that the closing price of Treatment 1 is higher than that of Treatment 2. The test results show that the closing price of Treatment 1 is lower than that of the other treatments. These results imply that theories that are considered bilateral oligopoly can describe the price formation of permits. However, our results show that the results of some cases are not consistent with the theoretical perspectives. In particular, the test results show that the closing price of Treatment 4 exhibits a similar trend with some treatments. The gap in the theoretical price between Treatments 4 and 6 is small. Thus, the test result is consistent. However, the theoretical convergence price of Treatment 4 differs from Treatments 7, 8 and 9. However, the test results show that the price trends between Treatment 4 and Treatments 7, 8 and 9 are the same. These results imply that the curvature of the market power of the seller is smaller than the theoretical perspective. However, nearly all test results agree with the theoretical perspective of the NCE and SA models.

Analysis and interpretation of experimental market data can be difficult to conduct because each market often exhibits a convergence process, which is not consistent with theoretical predictions. To investigate the convergence process in the experimental market, Noussair, Plott, and Riezman (1995) and Myagkov and Plott (1997) suggest an econometric model that explicitly makes use of data on trading prices. In this study, we apply this econometric model to estimate the convergence process of the permit price of each treatment. Specifically, the model for estimation is given by

$$p_{it} = \sum_{j=1}^{n} \beta_j D_j \left(\frac{1}{t}\right) + \alpha \left(\frac{t-1}{t}\right) + u_{it}, \tag{38}$$

where p_{it} is the permit price of period t in session i, D_j is a dummy variable that takes the value of 1 for session j and zero otherwise, β_j is a parameter that indicates a price level at the starting point of the convergence process, α is the price level at convergence, and u_{it} is a random disturbance term that is assumed to be distributed normally with zero mean. If $t = 1$, the value of the dependent variable, p_{it}, is equal to β_j for session j. The parameter α is the asymptote of p_{it}. As t gets large, the weight of β_1 becomes small because $1/t$ approaches zero, while the weight of α becomes large because $(t-1)/t$ approaches 1. For the price variable, we use both the median of permit trading prices and the permit price at the end of each trading period. We allow for a first-order serial correlation and heteroscedasticity in the estimation.

Table 5A presents the estimation results for the closing price of permits and Table 5B for the median price of permits in each period. Overall, there is little difference in the ability to predict the equilibrium price between two models of bilateral oligopoly. For the closing price, we cannot reject the null hypothesis that indicates the equality of the observed price with the price predicted by

Table 2
Theoretical predictions.

Treatment	Price	Total trade	Change in sellers' profits	Change in buyers' profits	Total trade relative to CE	Absolute values of Lerner index		Efficiency relative to CE
						Sellers	Buyers	
Panel A: Theoretical predictions: share auction (SA) model.								
1	116.7	10	−258	108	50%	10.0%	15.7%	75.0%
2	111.3	14	−507	213	50%	14.6%	23.1%	75.0%
3	122.0	6	−93	39	50%	14.6%	23.1%	75.0%
4	143.3	10	108	−258	50%	12.8%	8.2%	75.0%
5	148.7	14	213	−507	50%	17.3%	11.0%	75.0%
6	138.0	6	39	−93	50%	8.0%	5.1%	75.0%
7	130.0	10	−25	−25	50%	3.8%	3.8%	75.0%
8	130	14	−49	−49	50%	5.4%	5.4%	75.0%
9	130	6	−9	−9	50%	2.3%	2.3%	75.0%
Panel B: Theoretical predictions: noncompetitive equilibrium (NCE) model.								
1	123.3	14.5	−135	90	72.5%	5.7%	7.6%	92.5%
2	120.6	20.3	−264	176	72.5%	8.1%	10.9%	92.5%
3	126.0	8.7	−48	32	72.5%	3.3%	4.5%	92.5%
4	136.7	14.5	90	−135	72.5%	6.9%	5.1%	92.5%
5	139.4	20.3	176	−264	72.5%	9.5%	7.0%	92.5%
6	134.0	8.7	32	−48	72.5%	4.2%	3.1%	92.5%
7	130.0	13.3	−11	−11	66.6%	2.6%	2.6%	88.9%
8	130.0	18.7	−22	−22	66.6%	3.6%	3.6%	88.9%
9	130.0	8.0	−4	−4	66.6%	1.5%	1.5%	88.9%
Panel C: Theoretical predictions: supply function equilibrium (SFE) model.								
7	130.0	15	−6	−6	75.0%	1.9%	1.9%	93.7%
8	130.0	21	−12	−12	75.0%	2.7%	2.7%	93.7%
9	130.0	9	−2	−2	75.0%	1.2%	1.2%	93.7%

Panel D: Theoretical predictions: competitive equilibrium

Treatment	Price	Total trade	Sellers' abatement cost sales of permits	Buyers' abatement cost
1	130.0	20	6600	2600
2	130.0	28	5560	3640
3	130.0	12	7640	1560
4	130.0	20	3400	2600
5	130.0	28	2360	3640
6	130.0	12	4440	1560
7	130.0	20	3400	2600
8	130.0	28	2360	3640
9	130.0	12	4440	1560

Panel A Note: CE denotes competitive equilibrium. The absolute value of the Lerner index is $|(p - k')/p|$ for a buyer and $|(p - \kappa')/p|$ for a seller. The larger this value becomes, the larger the market power each trader exerts.
Panel B: Note: CE denotes competitive equilibrium.
Panel C Notes: CE denotes competitive equilibrium. The SFE is applicable only when all traders have an identical slope of the marginal abatement cost function (Treatments 7 to 9).
Panel D Note: In this calculation, we hypothesize the market situation of 4 participants (two sellers and two buyers). Thus, "Sellers' abatement cost–sales of permits" and "Buyers' abatement cost" represent the sum of the buyers and sellers, respectively.

either the SA or NCE model of bilateral oligopoly in all treatments. For the median price, this null hypothesis cannot be rejected in Treatments 1, 2, 3 and 6. These results imply that the observed price exhibits convergence to the price predicted by the theoretical bilateral oligopoly model. The estimated value of α varies across treatments. When the buyer's market power is larger than the seller's market power, the estimated value of α is found to be lower than the price at competitive equilibrium, as shown in Treatments 1, 2 and 3. In contrast, for Treatments 4 and 5, the estimated value of α is found to be higher than the competitive price. Our estimation result based on the closing price shows a lower value of α than the competitive benchmark in Treatment 6. However, the results of the convergence test based on median price show a higher value of α than the competitive benchmark. These estimates of converged prices are consistent with hypotheses regarding the bilateral oligopoly models.

4.2. Allocative efficiency and market power

We compare the adverse effects of market power on allocative efficiency across all treatments using the ratio of an increase in aggregate profits due to emissions trading under bilateral oligopoly to that under competitive equilibrium. This ratio is shown in Fig. 2 and Table 6. While the efficiency ratio increased as the trading period proceeded in all treatments, there seems to be some

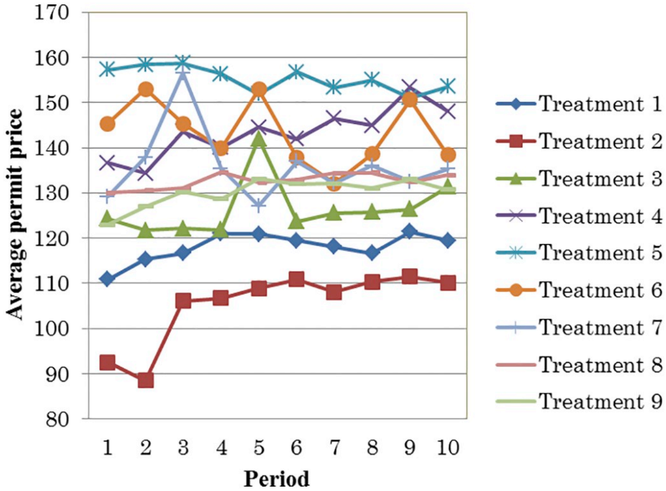

Fig. 1. Average permit price in each period.

Table 3
Average price of permits.

	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
Periods 1 to 5	117.0	100.6	126.4	139.8	156.5
Periods 6 to 10	119.0	110.2	126.6	146.9	153.9
All periods	118.0	105.4	126.5	143.4	155.2

	Treatment 6	Treatment 7	Treatment 8	Treatment 9
Periods 1 to 5	147.3	137.2	131.7	128.4
Periods 6 to 10	140.5	134.6	133.7	131.8
All periods	143.4	135.9	132.7	130.6

difference in the ratio across treatments. In fact, as shown in Table 7, the Mann-Whitney test with the null hypothesis that probability distributions of the efficiency ratio are identical across treatments indicated that the difference between Treatment 5 and any other treatment was statistically significant. The efficiency ratio in the last period of trading was close to that predicted by the SA bilateral oligopoly model in all treatments except Treatment 5. The efficiency ratio predicted by the NCE model was close to that in the last period of trading in Treatment 5. Thus, the market power of all traders reduced allocative efficiency in emissions permit trading, as indicated by the bilateral oligopoly models.

Finally, we analyze the effectiveness of the market power of each subject. Subjects with market power could increase their total profit in the 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 the supracompetitive total profit at the market power benchmark (Sturm, 2008). Specifically, as an illustrative example, we apply the NCE model to compute $M = (\pi - \pi^{CE})/(\pi^{NCE} - \pi^{CE})$, where π is the realized total profit of the market power subjects, π^{CE} is their total profit under perfect competition, and π^{NCE} is their total profit predicted by the NCE model. The index M is 1 if the realized profit of the market power subjects is equal to their total profit predicted by the NCE model ($\pi = \pi^{NE}$). However, it may exceed 1 in 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 predicted by the NCE model.

Fig. 3 shows the index of market power effectiveness in all treatments for the NCE model.[6] For Treatments 7, 8 and 9, the index of market power effectiveness was not computed because no subject was considered to be on the "strong market side". Because Proposition 1 implies that the market power of buyers (subjects A and B) exceeds that of sellers (subjects C and D) in Treatments 1, 2 and 3, the market power subjects are subjects A and B, and their total profit is used to compute M. For Treatment 1, M is below 1 in most periods. For Treatment 2, M is far below 1 in the early periods but exceeds 1 in the last four periods. In Treatment 3, M exceeds 1 in some periods. However, M is not stable throughout all periods. Turning to Treatments 4, 5 and 6, the market power of sellers (subjects C and D) exceeds that of buyers (subjects A and B). Thus, the market power subjects are subjects C and D in these treatments. For Treatment 4, M falls below 1 in early periods and converges to 1 in the last two periods. In Treatment 6, M is not stable throughout all periods. For Treatment 5, M exceeds 1 in most periods.

[6] As shown in Fig. 3, we exclude outlier session data in Treatment 6. In this experiment, each session consists of 4 members. Thus, the inclusion of outliers in this experimental session may lead to anomalous values. We provide details about the outlier effect in Appendix B.

Table 4
Results of a Mann-Whitney test for the closing price of permits.

	Entire period	*p*-value
Treatment 1 vs Treatment 2	2.935***	0.0003
Treatment 1 vs Treatment 3	−2.602***	0.0093
Treatment 1 vs Treatment 4	−4.721***	0.0000
Treatment 1 vs Treatment 5	−7.746***	0.0000
Treatment 1 vs Treatment 6	−5.091***	0.0000
Treatment 1 vs Treatment 7	−4.596***	0.0000
Treatment 1 vs Treatment 8	−6.001***	0.0000
Treatment 1 vs Treatment 9	−4.820***	0.0000
Treatment 2 vs Treatment 3	−6.348***	0.0000
Treatment 2 vs Treatment 4	−7.822***	0.0000
Treatment 2 vs Treatment 5	−9.134***	0.0000
Treatment 2 vs Treatment 6	−7.600***	0.0000
Treatment 2 vs Treatment 7	−7.883***	0.0000
Treatment 2 vs Treatment 8	−8.828***	0.0000
Treatment 2 vs Treatment 9	−8.484***	0.0000
Treatment 3 vs Treatment 4	−2.822***	0.0048
Treatment 3 vs Treatment 5	−6.963***	0.0000
Treatment 3 vs Treatment 6	−3.692***	0.0002
Treatment 3 vs Treatment 7	−2.782***	0.0054
Treatment 3 vs Treatment 8	−4.912***	0.0000
Treatment 3 vs Treatment 9	−3.321***	0.0009
Treatment 4 vs Treatment 5	−5.636***	0.0000
Treatment 4 vs Treatment 6	−1.638	0.1015
Treatment 4 vs Treatment 7	0.100	0.9205
Treatment 4 vs Treatment 8	−1.340	0.1802
Treatment 4 vs Treatment 9	0.310	0.7567
Treatment 5 vs Treatment 6	3.134***	0.0017
Treatment 5 vs Treatment 7	4.907***	0.0000
Treatment 5 vs Treatment 8	5.117***	0.0000
Treatment 5 vs Treatment 9	6.127***	0.0000
Treatment 6 vs Treatment 7	1.306	0.1917
Treatment 6 vs Treatment 8	0.390	0.6969
Treatment 6 vs Treatment 9	1.450	0.1471
Treatment 7 vs Treatment 8	−1.885*	0.0595
Treatment 7 vs Treatment 9	−0.202	0.8399
Treatment 8 vs Treatment 9	2.614***	0.0089

Note: * indicates significance at the 10% level, ** indicates significance at the 5% level, and *** indicates significance at the 1% level. We also test the first half (from periods 1 to 5) and second half (from periods 6 to 10). These test results are shown in Appendix B.

Table 5A
Convergence test of permit prices (closing price).

Treatment	α (*p-value*)	CE price (*p-value of H_0*)	SA price (*p-value of H_0*)	NCE price (*p-value of H_0*)
1	120.0(0.00)	130 0.0(0.00)	116.7(0.15)	123.3(0.15)
2	110.5(0.00)	130.0(0.00)	111.3(0.69)	120.6(0.00)
3	127.2(0.00)	130.0(0.11)	122.0(0.00)	126.0(0.48)
4	142.5(0.00)	130.0(0.00)	143.3(0.68)	136.7(0.00)
5	138.3(0.00)	130.0(0.00)	148.7(0.00)	139.4(0.29)
6	127.4(0.00)	130.0(0.77)	138.0(0.22)	134.0(0.45)
7	130.8(0.00)	130.0(0.14)	130.0(0.14)	130.0(0.14)
8	132.1(0.00)	130.0(0.06)	130.0(0.06)	130.0(0.06)
9	131.3(0.00)	130.0(0.15)	130.0(0.15)	130.0(0.15)

Notes: CE, SA, and NCE denote competitive equilibrium, share auction, and noncompetitive equilibrium, respectively. H_0 denotes a null hypothesis that indicates the equality of estimated value of α with the CE price, SA price or NCE price. The *p*-value of H_0 is estimated by a Wald statistic.

5. Conclusion

Our results suggest that theoretical bilateral oligopoly models can describe market outcomes of emissions trading better than traditional models. The equilibrium price of our experiment is consistent with that of bilateral oligopoly models of emissions trading. The effects of the slope of the marginal abatement cost function on market power in laboratory experiments are also found to be consistent with those predicted by the theoretical bilateral oligopoly model. How market power is exercised depends on the curvature of the abatement cost function. If the marginal abatement cost function of buyers (sellers) is less steep than that of sellers (buyers), the

Table 5B
Convergence test of permit prices (median price).

Treatment	*α* (*p- value*)	CE price (*p-value of* H_0)	SA price (*p-value of* H_0)	NCE price (*p-value of* H_0)
1	123.5(0.00)	130 0.0(0.00)	116.7(0.00)	123.3(0.87)
2	112.0(0.00)	130.0(0.00)	111.3(0.75)	120.6(0.00)
3	125.3(0.00)	130.0(0.00)	122.0(0.00)	126.0(0.46)
4	150.4(0.00)	130.0(0.00)	143.3(0.00)	136.7(0.00)
5	154.1(0.00)	130.0(0.00)	148.7(0.00)	139.4(0.00)
6	136.9(0.00)	130.0(0.00)	138.0(0.47)	134.0(0.07)
7	131.3(0.00)	130.0(0.00)	130.0(0.00)	130.0(0.00)
8	133.5(0.00)	130.0(0.00)	130.0(0.00)	130.0(0.00)
9	132.5(0.00)	130.0(0.00)	130.0(0.00)	130.0(0.00)

Notes: CE, SA, and NCE denote competitive equilibrium, share auction, and noncompetitive equilibrium, respectively. H_0 denotes a null hypothesis that indicates the equality of the estimated value of α with the CE price, SA price or NCE price. The *p*-value of H_0 is estimated by a Wald statistic.

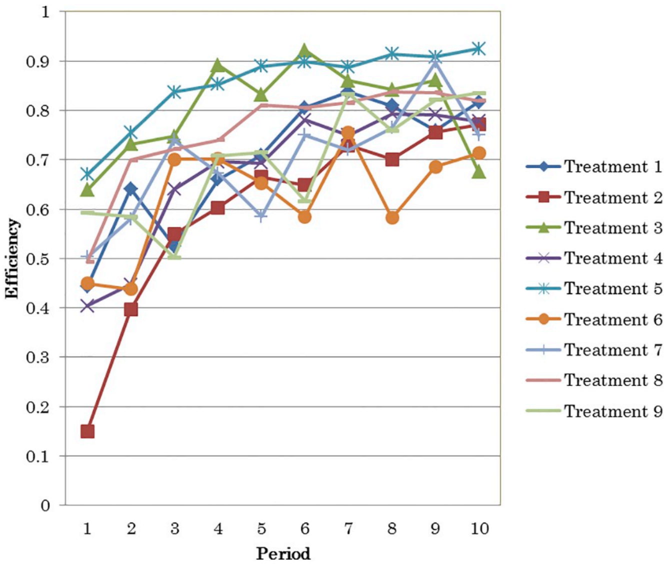

Fig. 2. Efficiency relative to competitive equilibrium in each period.

Table 6
Efficiency relative to competitive equilibrium.

	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
Periods 1–5	0.601	0.473	0.77	0.576	0.801
Periods 6–10	0.780	0.721	0.83	0.778	0.907
All periods	0.691	0.597	0.80	0.667	0.854

	Treatment 6	Treatment 7	Treatment 8	Treatment 9
Periods 1–5	0.589	0.625	0.69	0.62
Periods 6–10	0.665	0.737	0.82	0.77
All periods	0.627	0.681	0.76	0.70

price of permits is lower (higher) than that under perfect competition. This is because the market power of buyers (sellers) exceeds that of sellers (buyers). The price of permits is close to the perfect competitive price when all traders have the same slope of the marginal abatement cost function.

When the market power of buyers exceeds that of sellers, an increase in sellers' initial endowment of emissions permits relative to buyers' initial endowment enhances buyers' market power, thereby lowering the permit price. In contrast, when the market power of sellers exceeds that of buyers, an increase in sellers' initial endowment of permits relative to buyers' initial endowment enhances sellers' market power, thereby raising the market price. The persistent divergence in the equilibrium price of emissions permits from the competitive level, which occurs because of the difference in the slope of the marginal abatement cost function and the initial endowment of emissions permits, is consistent with the literature on laboratory experiments of emissions trading (Sturm, 2008).

Table 7
Results of a Mann-Whitney test for the efficiency ratio.

	All periods	Periods 1 to 5	Periods 6 to 10
Treatment 1 vs Treatment 2	1.884[a]	1.925[a]	1.27
Treatment 1 vs Treatment 3	−4.168[c]	3.493[c]	−2.566[b]
Treatment 1 vs Treatment 4	0.756	0.313	1.776[a]
Treatment 1 vs Treatment 5	−2.948[c]	−2.402[b]	−2.611[c]
Treatment 1 vs Treatment 6	1.512	−0.375	1.424
Treatment 1 vs Treatment 7	0.128	−0.375	0.525
Treatment 1 vs Treatment 8	−2.102[b]	−2.272[b]	−0.722
Treatment 1 vs Treatment 9	−0.942	−0.645	−0.655
Treatment 2 vs Treatment 3	−5.632[c]	−4.562[c]	−3.812[c]
Treatment 2 vs Treatment 4	−1.361	−1.149	−2.193[b]
Treatment 2 vs Treatment 5	−3.326[c]	−2.611[c]	−2.611[c]
Treatment 2 vs Treatment 6	0.076	−2.098[b]	0.327
Treatment 2 vs Treatment 7	−1.863[a]	−2.252[b]	0.43
Treatment 2 vs Treatment 8	−3.597[c]	−3.359[c]	−2.262[b]
Treatment 2 vs Treatment 9	−2.796[c]	−2.281[b]	−2.157[b]
Treatment 3 vs Treatment 4	4.377[c]	3.243[c]	3.370[c]
Treatment 3 vs Treatment 5	−0.150	−0.308	0.164
Treatment 3 vs Treatment 6	4.417[c]	2.873[c]	3.490[c]
Treatment 3 vs Treatment 7	3.816[c]	2.695[c]	2.918[c]
Treatment 3 vs Treatment 8	3.673[c]	2.310[b]	2.860[c]
Treatment 3 vs Treatment 9	2.774[c]	2.484[b]	0.135
Treatment 4 vs Treatment 5	−2.948[c]	−2.193[b]	−2.611[c]
Treatment 4 vs Treatment 6	1.209	−0.327	1.165
Treatment 4 vs Treatment 7	0.031	−0.327	0.135
Treatment 4 vs Treatment 8	−1.232	−1.328	−0.751
Treatment 4 vs Treatment 9	−1.355	−0.683	−1.704[a]
Treatment 5 vs Treatment 6	3.326[c]	3.310[c]	3.994[c]
Treatment 5 vs Treatment 7	4.478[c]	3.378[c]	3.094[b]
Treatment 5 vs Treatment 8	4.591[c]	2.762[c]	3.995[c]
Treatment 5 vs Treatment 9	3.151[c]	2.811[c]	1.791[a]
Treatment 6 vs Treatment 7	−0.754	0.010	−1.030
Treatment 6 vs Treatment 8	−2.229[a]	−1.194	−1.829
Treatment 6 vs Treatment 9	−1.594	−0.313	−1.931[a]
Treatment 7 vs Treatment 8	−1.548	−1.434	−0.664
Treatment 7 vs Treatment 9	−0.797	−0.067	−1.001
Treatment 8 vs Treatment 9	−0.328	0.616	−1.185

[a] Indicates significance at the 10% level.
[b] Indicates significance at the 5% level.
[c] Indicates significance at the 1% level.

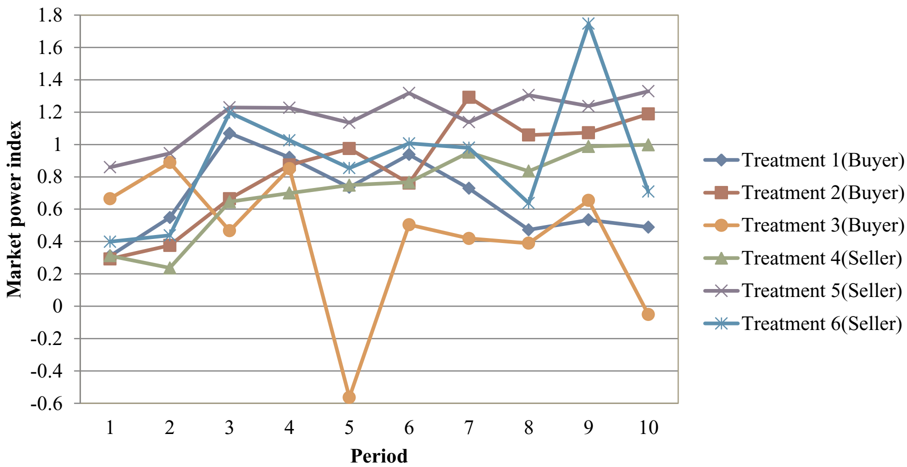

Fig. 3. Index of market power effectiveness: the NCE model.

Initial endowment of the tradable permits is one of the critical policy issues for the policymaker. Most of the emissions trading scheme, such as EU-ETS and China-ETS, discussed how to allocate the initial endowment for a long time (Zhou & Wang, 2016). Initial endowment of CO_2 emissions permits critically affects the energy use of the regulated region (Kara et al., 2008). Also, the performance of emissions permits market affects the several kinds of other economic activity, such as trade (Takarada, Tsubuku, & Okimoto, 2017). Therefore, we need more carefully to understand how to improve emissions trading schemes. Our results contribute to the discussion about the fundamental problem of the emissions trading system. While the main objective of emissions trading system in this study is to control the CO_2 emissions, it could be applied to the efficient control of other pollutants. The bilateral oligopoly model well describes regionally tradable permit schemes that consist of a small number of participants. For example, Cason et al. (2003) focus on the trading rights of water pollution in Port Phillip Bay where the trading market was dominated by a small number of participants.

The literature on trading in the laboratory experiment tries to reveal the effect of market power that could be exerted by a limited number of traders. The literature suggests how to control market power associated with the initial allocation of permits. In this respect, our results imply that the policymaker needs to consider each participant's abatement technology (i.e., the curvature of the abatement cost function) when the government allocates the initial endowment of tradable permits to a small number of traders. Also, our finding implies that the double auction cannot control the market power of each participant. Some previous studies discussed how to design an auction mechanism that would improve allocative efficiency in the market when there is much concern about market power. Some researchers argue that a double auction mechanism could control market power of traders (Cason et al., 2003; Godby, 1999; Ledyard & Szakaly-Moore, 1994). However, the previous studies also found that double auction could not entirely control it (Muller et al., 2002; Sturm, 2008). Our research finds that double auction cannot control the market power under bilateral oligopoly.

As suggested by Kotani et al. (2019), uniform price auction is effective to constrain market power in emissions trading. Uniform price auction may achieve more efficient outcome than double auction under bilateral oligopoly, because uniform price auction imposes a restriction on strategies that could be chosen by traders exhibiting market power. Also, inter-regionally trade system of permits has a possibility to decrease the market power of each participant. For example, Higashida, Tanaka, and Managi (2019) suggest the new inter-regionally trade system that can adjust the difference of each regional environmental value.

Furthermore, understanding the behavior of bilateral oligopolists can contribute to the efficient design of energy markets such as wholesale electricity markets. In many countries, it is often the case that a small number of electricity companies dominate the wholesale market of electricity. A better understanding of bilateral oligopoly is useful for the energy markets to be operated efficiently.

Acknowledgement

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Appendix A

A.1. Derivation of Eqs. (15), (16), and (17) in Section 2

First, a boundary condition indicates that the price at zero trading (i.e., P_0 and Π_0) is equal to the marginal abatement cost at zero trading:

$$P_0 = c_0 + c(x - z_b) \tag{A1}$$

$$\Pi_0 = \gamma_0 + \gamma(x - z_s). \tag{A2}$$

Inserting (A1) and (A2) into (3) and (4) yields (9) and (10), respectively.

Second, the first-order conditions of (7) and (8) are

$$c_0 + c(x - z_b - y_i) = -\left(\frac{y_i}{n}\right)\Pi' + \Pi\left[-\frac{y_i + (n-1)y}{n}\right] \tag{A3}$$

$$\gamma_0 + \gamma(x - z_s - \psi_j) = -\left(\frac{\psi_j}{n}\right)P' + P\left[-\frac{\psi_j + (n-1)\psi}{n}\right], \tag{A4}$$

where P' and Π' denote the derivatives of P and Π, respectively. From (9) and (10), $P' = -q$ and $\Pi' = -\eta$, respectively. Inserting these and the market clearing condition that $n(\psi + y) = 0$ into (A3) and (A4) yields the following:

$$c_0 + c(x - z_b - y^A) = \left(\frac{y^A}{n}\right)\eta + \Pi(\psi^A) \tag{A5}$$

$$\gamma_0 + \gamma(x - z_s - \psi^A) = \left(\frac{\psi^A}{n}\right)q + P(y^A) \tag{A6}$$

where y^A and ψ^A denote the optimal trade for each buyer and each seller, respectively. Inserting $P(y^A)$ in (9) and $\Pi(\psi^A)$ in (10) into (A5) and (A6) yields the following system of equations:

$$c_0 + c(x - z_b - y^A) = \left(\frac{y^A}{n}\right)\eta + [\gamma_0 + \gamma(x - z_s) - \eta\psi^A] \tag{A7}$$

$$\gamma_0 + \gamma(x - z_s - \psi^A) = \left(\frac{\psi^A}{n}\right)q + [c_0 + c(x - z_b) - qy^A] \tag{A8}$$

The solution to the system of Eqs. (A7) and (A8) implies the optimal trade in (11) and (12), respectively.

In equilibrium, the price for buyers must be equal to the price for sellers. From $P(y^A)$ in (9) and $\Pi(\psi^A)$ in (10), (11), and (12), the parameters η and q can be rewritten as in (13) and (14). Inserting (13) and (14) into (11) and (12) yields the equilibrium trade in (16) and (17), respectively. Finally, the market price in (15) is derived by inserting (16) and (17) into (9) and (10), respectively.

A.2. LDFE model of Wirl (2009)

In our setup, the slopes of the demand functions for permits in the LDFE model of Wirl (2009, Section 5), denoted by e for buyers and ε for sellers, are obtained by solving the system of the following equations that correspond to Eqs. (45) and (47) in Wirl (2009):

$$e = (1 + ce)[(n - 1)e + n\varepsilon] \tag{A9}$$

$$\varepsilon = (1 + \gamma\varepsilon)[ne + (n - 1)\varepsilon] \tag{A10}$$

The first-order condition in the NCE model of Lange, 2012, eq. 3 can be written as.

$$f(p) = [p - c(x - z_b - f(p)) - c_0][(n - 1)f'(p) + n\varphi'(p)] \tag{A11}$$

for buyers and

$$\varphi(p) = [p - \gamma(x - z_s - \varphi(p)) - \gamma_0][nf'(p) + (n - 1)\varphi'(p)] \tag{A12}$$

for sellers in our setup. Differentiating (A11) and (A12) with respect to the price yields the system of the following equations, whose solutions lead to the slopes of the demand functions for permits in the NCE model:

$$f'(p) = [1 + cf'(p)][(n - 1)f'(p) + n\varphi'(p)] \tag{A13}$$

and

$$\varphi'(p) = [1 + \gamma\varphi'(p)][nf'(p) + (n - 1)\varphi'(p)] \tag{A14}$$

Since demand functions $f(p)$ and $\varphi(p)$ are linear in their parameters, the solutions to the system of Eqs. (A13) and (A14) coincide with the solutions to the system of Eqs. (A9) and (A10). Thus, the slopes of the demand functions for permits in the LDFE model are equal to those in the NCE model.

Given the slopes of the demand functions, the intercepts of the demand functions for permits in the LDFE model of Wirl, 2009, Section 5, denoted by d for buyers and δ for sellers, are obtained by solving the following equations, which correspond to Eqs. (44) and (46) in Wirl (2009):

$$d = [c(d - x + z_b) - c_0][(n - 1)e + n\varepsilon] \tag{A15}$$

$$\delta = [\gamma(\delta - x + z_s) - \gamma_0][ne + (n - 1)\varepsilon] \tag{A16}$$

From (A11) and (A12), with $p = 0$, the intercepts of the demand functions for permits in the NCE model, denoted by ρ for buyers and ς for sellers, are obtained by the solution of the following equations:

$$\rho = [c(\rho - x + z_b) - c_0][(n - 1)f'(p) + n\varphi'(p)] \tag{A17}$$

$$\varsigma = [\gamma(\varsigma - x + z_s) - \gamma_0][nf'(p) + (n - 1)\varphi'(p)] \tag{A18}$$

Since the slopes of the demand functions for permits in the LDFE model are equal to those in the NCE model, from (A15) to (A18), $d = \rho$ and $\delta = \varsigma$. Thus, the demand functions for permits in the LDFE model coincide with those in the NCE model in our setup.

A.3. The equilibrium quantity of trade when the number of buyers is different from that of sellers: the case that $c = \gamma$

For the case that $c = \gamma$ and $nb \neq ns$, the equilibrium trade under the i-th model of bilateral oligopoly is given by.

$y^i = K^i[\beta(z_s - z_b) + c_0 - \gamma_0],\ i = A, N, S$

$\Psi^i = -H^i[\beta(z_s - z_b) + c_0 - \gamma_0],\ i = A, N, S$

where

$$K^A \equiv \frac{n_b n_s - 1}{cn_b(n_b + n_s + 2)},\quad K^N \equiv \frac{n_s(n_b + n_s - 2)}{c(n_b + n_s)(n_b + n_s - 1)},\quad K^S \equiv \frac{n_s(n_b + n_s - 1)}{c(n_b + n_s)^2},$$

$$H^A \equiv \frac{n_b n_s - 1}{\gamma n_s(n_b + n_s + 2)},\quad H^N \equiv \frac{n_b(n_b + n_s - 2)}{\gamma(n_b + n_s)(n_b + n_s - 1)},\quad H^S \equiv \frac{n_b(n_b + n_s - 1)}{\gamma(n_b + n_s)^2}.$$

The above equations imply that for $c = \gamma$, the equilibrium trade under the SA model is the smallest among the three models with $nb \neq ns$.

A.4 Proof of Proposition 1.

In the SA model, from (A3) and (A4), the markup in equilibrium with $P = \Pi$ can be written as.

$$p^A - k' = \Pi' y^A/n = -\eta y^A/n \tag{A19}$$

for buyers and.

$$p^A - \kappa' = P'\psi^A/n = -q\psi^A/n \tag{A20}$$

for sellers.

From (16) and (17), the markup in (A19) and (A20) can be rewritten as.

$$pA - k' = -\left[\frac{c + n\gamma}{n(n+1)(c+\gamma)}\right](\gamma z_s - cz_b + c_0 - \gamma_0) \tag{A21}$$

for buyers and

$$pA - \kappa' = \left[\frac{nc + \gamma}{n(n+1)(c+\gamma)}\right](\gamma z_s - cz_b + c_0 - \gamma_0) \tag{A22}$$

for sellers. (A21) and (A22) indicate the following:

$$\mid p^A - k' \mid - \mid p^A - ' \mid = \left[\frac{(\gamma - c)(n-1)}{n(n+1)(c+\gamma)}\right](\gamma z_s - cz_b + c_0 - \gamma_0). , \tag{A23}$$

where $|p^A - k'|$ and $|p^A - \kappa'|$ denote the absolute value of $p^A - k'$ and that of $p^A - \kappa'$, respectively.

(A23) implies

$$\begin{aligned} &|p^A - k'| > |p^A - \kappa'| \; if c < \gamma, \\ &|p^A - k'| = |p^A - \kappa'| \; if c = \gamma, \text{and} \\ &|p^A - k'| < |p^A - \kappa'| \; if c > \gamma. \end{aligned} \tag{A24}$$

In the NCE model, from (20) and (21), the markup for buyer i and that for seller j can be written as

$$p^N - k' = -y^N/mb = -\left[\frac{M_s}{(M_b + M_s)(1 + cm_b)}\right][c_0 - \gamma_0 + c(x - z_b) - \gamma(x - z_s)] \tag{A25}$$

for buyers and

$$p^N - \kappa' = -\psi^N/ms = \left[\frac{M_b}{(M_b + M_s)(1 + \gamma m_s)}\right][c_0 - \gamma_0 + c(x - z_b) - \gamma(x - z_s)], \tag{A26}$$

for sellers. (A25) and (A26) indicate that

$$\mid p^N - k' \mid - \mid p^N - \kappa' \mid = \left[\frac{m_s - m_b}{(M_b + M_s)(1 + cm_b)(1 + \gamma m_s)}\right][c_0 - \gamma_0 + c(x - z_b) - \gamma(x - z_s)] \tag{A27}$$

Since a larger slope of the marginal abatement cost function is associated with a larger m_i (Lange, 2012, Section 2.2),

$$\gamma \overset{>}{\underset{<}{-}} c \Leftrightarrow m_s \overset{>}{\underset{<}{-}} m_b$$

Thus, (A27) implies

$| p^N - k'| > | p^N - \kappa'|$ if $c < \gamma$,

$| p^N - k'| = | p^N - \kappa'|$ if $c = \gamma$, and

$| p^N - k'| < | p^N - \kappa'|$ if $c > \gamma$

Q.E.D.

A.5 Proof of Proposition 2

In the SA model, given the total amount of permits, Z, differentiating the equilibrium price of permits in (15) with respect to the initial allocation of permits for buyers and sellers yields

$$\left.\frac{\partial p^A}{\partial z_b}\right|_{Z \text{ is given}} = \frac{-c(c + n\gamma) + \gamma(nc + \gamma)}{(n+1)(c+\gamma)} = \frac{\gamma - c}{n+1} \tag{A28}$$

$$\left.\frac{\partial p^A}{\partial z_s}\right|_{Z \text{ is given}} = \frac{c(c + n\gamma) - \gamma(nc + \gamma)}{(n+1)(c+\gamma)} = \frac{c - \gamma}{n+1} \tag{A29}$$

Thus, (A28) and (A29) imply

$$\left.\frac{\partial p^A}{\partial z_b}\right|_{Z \text{ is given}} > 0, \left.\frac{\partial p^A}{\partial z_s}\right|_{Z \text{ is given}} < 0 \text{ if } \gamma > c,$$
$$\left.\frac{\partial p^A}{\partial z_b}\right|_{Z \text{ is given}} = 0, \left.\frac{\partial p^A}{\partial z_s}\right|_{Z \text{ is given}} = 0 \text{ if } \gamma = c, \text{ and.}$$
$$\left.\frac{\partial p^A}{\partial z_b}\right|_{Z \text{ is given}} < 0, \left.\frac{\partial p^A}{\partial z_s}\right|_{Z \text{ is given}} > 0 \text{ if } \gamma < c.$$

In the NCE model, given the total amount of permits, Z, differentiating the equilibrium price of permits in (24) with respect to the initial allocation of permits for buyers and sellers yields

$$\left.\frac{\partial p^N}{\partial z_b}\right|_{Z \text{ is given}} = \frac{-M_b c + M_s \gamma}{M_b + M_s} = \frac{\gamma m_s - c m_b}{(M_b + M_s)(1 + c m_b)(1 + \gamma m_s)} \tag{A30}$$

$$\left.\frac{\partial p^N}{\partial z_s}\right|_{Z \text{ is given}} = \frac{-M_s \gamma + M_b c}{M_b + M_s} = \frac{c m_b - \gamma m_s}{(M_b + M_s)(1 + c m_b)(1 + \gamma m_s)} \tag{A31}$$

where $M_b \equiv m_b/(1 + c m_b)$ and $M_s \equiv m_s/(1 + \gamma m_s)$.

Since a larger slope of the marginal abatement cost function is associated with a larger m_i (Lange, 2012, Section 2.2),

$$\gamma \underset{<}{\overset{>}{-}} c \Leftrightarrow m_s \underset{<}{\overset{>}{-}} m_b$$

Thus, (A30) and (A31) imply.

$$\left.\frac{\partial p^N}{\partial z_b}\right|_{Z \text{ is given}} > 0, \left.\frac{\partial p^N}{\partial z_s}\right|_{Z \text{ is given}} < 0 \ \text{ if } \gamma > c,$$

$$\left.\frac{\partial p^N}{\partial z_b}\right|_{Z \text{ is given}} = 0, \ \left.\frac{\partial p^N}{\partial z_s}\right|_{Z \text{ is given}} = 0 \ \text{ if } \gamma = c, \text{and}$$

$$\left.\frac{\partial p^N}{\partial z_b}\right|_{Z \text{ is given}} < 0, \ \left.\frac{\partial p^N}{\partial z_s}\right|_{Z \text{ is given}} > 0 \ \text{ if } \gamma < c.$$

Q.E.D.

A.6 Proof of Proposition 3.

In the case that $c = \gamma$, the equilibrium price of permits in the SA model becomes

$$p^A = \frac{c_0 + \gamma_0}{2} + \beta\left(x - \frac{Z}{2n}\right) = \mu_0 + \beta(x - z_a) \tag{A32}$$

while that in the NCE model becomes

$$p^N = \frac{c_0 + \gamma_0}{2} + \beta\left(x - \frac{Z}{2n}\right) = \mu_0 + \beta(x - z_a), \tag{A33}$$

where $\beta = c = \gamma$. (A32) and (A33) imply that if $c = \gamma$, then $p^A = p^N = p^S$.

Under perfect competition, the equilibrium price of permits must be equal to the marginal abatement cost that is identical between the sellers and buyers in equilibrium. Since $k' = \kappa'$ and $n(y + \psi) = 0$ in competitive equilibrium, the equilibrium trade of permits under perfect competition is

$$y^* = \frac{c_0 - \gamma_0}{2\beta} + \frac{z_s - z_b}{2} \tag{A34}$$

for buyers and

$$\psi^* = \frac{\gamma_0 - c_0}{2\beta} + \frac{z_b - z_s}{2} \tag{A35}$$

for sellers. Inserting y^* (ψ^*) into the marginal abatement cost function for buyers (sellers) leads to the equilibrium price of permits under perfect competition:

$$p^* = \frac{c_0 + \gamma_0}{2} + \beta\left(x - \frac{Z}{2n}\right) = \mu_0 + \beta(x - z_a).$$

Thus, if $c = \gamma$, then $p^A = p^N = p^S = p^*$.

Q.E.D.

Appendix B. Results of a Mann-Whitney test for the closing price of permits (Periods 1 to 5 and Periods 6 to 10)

	Periods 1 to 5	p-value	Periods 6–10	p-value
Treatment 1 vs Treatment 2	1.665[a]	0.0959	2.504[b]	0.0123
Treatment 1 vs Treatment 3	1.564	0.1178	−1.922[a]	0.0546
Treatment 1 vs Treatment 4	−2.739[c]	0.0062	−3.568[c]	0.0004
Treatment 1 vs Treatment 5	−4.274[c]	0.0000	−5.970[c]	0.0000
Treatment 1 vs Treatment 6	−3.948[c]	0.0001	−2.868[c]	0.0041
Treatment 1 vs Treatment 7	−2.989[c]	0.0028	−3.327[c]	0.0009
Treatment 1 vs Treatment 8	−3.663[c]	0.0002	−4.721[c]	0.0000
Treatment 1 vs Treatment 9	−2.847[c]	0.0044	−3.791[c]	0.0002
Treatment 2 vs Treatment 3	−3.482[c]	0.0005	−5.103[c]	0.0000
Treatment 2 vs Treatment 4	−4.503[c]	0.0000	−5.943[c]	0.0000
Treatment 2 vs Treatment 5	−5.569[c]	0.0000	−6.764[c]	0.0000
Treatment 2 vs Treatment 6	−5.245[c]	0.0000	−4.802[c]	0.0000
Treatment 2 vs Treatment 7	−4.939[c]	0.0000	−5.532[c]	0.0000
Treatment 2 vs Treatment 8	−5.639[c]	0.0000	−6.482[c]	0.0000
Treatment 2 vs Treatment 9	−5.287[c]	0.0000	−6.178[c]	0.0000
Treatment 3 vs Treatment 4	−1.654[a]	0.0982	−2.221[b]	0.0263
Treatment 3 vs Treatment 5	−4.166[c]	0.0000	−5.185[c]	0.0000
Treatment 3 vs Treatment 6	−3.768[c]	0.0002	−1.709[a]	0.0875
Treatment 3 vs Treatment 7	−2.121[b]	0.0339	−1.8880[a]	0.0601
Treatment 3 vs Treatment 8	−3.332[c]	0.0009	−3.860[c]	0.0001
Treatment 3 vs Treatment 9	−2.089[b]	0.0367	−2.649[c]	0.0081
Treatment 4 vs Treatment 5	−3.143[c]	0.0017	−4.576[c]	0.0000
Treatment 4 vs Treatment 6	−2.706[c]	0.0068	0.063	0.9497
Treatment 4 vs Treatment 7	−0.581	0.5611	0.224	0.8230
Treatment 4 vs Treatment 8	−1.454	0.1460	−1.011	0.3119
Treatment 4 vs Treatment 9	−0.217	0.8280	0.305	0.7604
Treatment 5 vs Treatment 6	0.236	0.8135	3.840[c]	0.0001
Treatment 5 vs Treatment 7	2.130[b]	0.0331	4.223[c]	0.0000
Treatment 5 vs Treatment 8	2.393[b]	0.0167	4.161[c]	0.0000
Treatment 5 vs Treatment 9	3.203[c]	0.0014	4.855[c]	0.0000
Treatment 6 vs Treatment 7	1.771[a]	0.0766	−0.097	0.9230
Treatment 6 vs Treatment 8	1.811[a]	0.0702	−1.225	0.2205
Treatment 6 vs Treatment 9	2.567[b]	0.0103	−0.259	0.7957
Treatment 7 vs Treatment 8	−0.967	0.3334	−1.445	0.1484
Treatment 7 vs Treatment 9	−0.041	0.9676	0.093	0.9259
Treatment 8 vs Treatment 9	1.572	0.1159	2.435[b]	0.0149

Note.
[a] Indicates significance at the 10% level.
[b] Indicates significance at the 5% level.
[c] Indicates significance at the 1% level.

Appendix C. Details on market power index in Treatment 6

Table B.1 shows the market power index for each session of Treatment 6. In almost all sessions, the index is approximately 1. Some sessions have outliers because of bad trades caused by participant misunderstanding. However, the index of session 2 is very small compared with the indices of other sessions. It is possible that sellers in this session did not fully understand the experiment instructions. Compared to other treatments and sessions, the index value of session 2 is highly unusual. Therefore, we excluded the results from the data in Table 3. Fig. C.1 shows the trend of the market power index, including the results of session 2 in Treatment 6.

Table C.1
Market power index in each session (Treatment 6).

Period	Session							
	1	2	3	4	5	6	7	8
1	1.264	−9.679	0.396	0.538	−0.660	0.830	−0.538	0.962
2	1.236	−18.028	1.406	0.632	−1.198	1.094	−1.132	1.028
3	1.406	−1.255	0.670	0.679	0.481	0.802	3.330	1.009
4	1.613	−1.255	1.085	0.406	0.802	0.679	1.198	1.396
5	1.340	−10.368	1.057	0.623	0.217	0.943	0.660	1.142
6	1.349	−2.613	0.962	0.783	0.245	0.755	1.245	1.708
7	1.396	−1.245	1.217	0.519	0.255	0.934	1.330	1.208
8	1.377	−2.208	1.406	0.594	0.160	0.660	−0.717	0.981

(continued on next page)

Table C.1 (*continued*)

Period	Session							
	1	2	3	4	5	6	7	8
9	1.613	0.066	0.868	0.292	0.245	7.679	0.377	1.160
10	0.274	−6.142	1.236	0.453	0.236	0.745	0.019	2.000
Average	1.287	−5.273	1.030	0.552	0.078	1.512	0.577	1.259

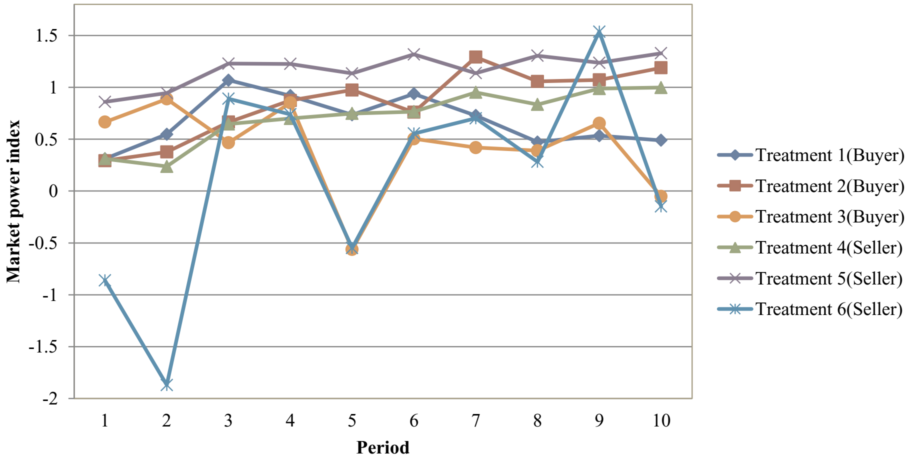

Fig. C.1. Index of market power effectiveness: the NCE model.
(Includes the results of session 2 in Treatment 6)

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