論文 (*Article*)

Analysis of CO_2 Emissions Trading Considering the Kyoto Protocol Using a Multi-Agent Model

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In this study, a multi-agent simulation model is constructed and international emissions trading (IET) of CO_2 considering the Kyoto Protocol is analyzed using it. Then, the results are compared with the "no IET" and the "theoretical IET". Unlike traditional economic methods, multi-agent models make analysis of complex social systems like emissions trading possible without strong assumptions. In the model, each country (region) behaves as an independent agent in the interactions and tries to abate CO_2 emissions with minimum cost through decision making between self-abatement and IET depending on its local information. In the trade, offer prices are determined based on marginal abatement cost functions and strategies, and offer amounts are determined based on CO_2 emissions and emissions rights.

As a result, although the results of each simulation are similar, the states of trade are continuously fluctuating. From the comparisons with the no IET and the theoretical IET, it is revealed that the costs and the self-abatement amounts of the developed countries become smaller, the profit of economies in transition become larger, and the total cost becomes smaller by introducing IET assuming bounded rationality. However, these effects are far below those of the theoretical IET.

Key Words : Multi-Agent Model, CO_2 Emissions Trading, Kyoto Protocol, Bounded Rationality, Marginal Abatement Cost Function

1. Introduction

Although the first commitment period of the Kyoto Protocol (2008-2012) is soon coming, climate change policies and measures under the Kyoto Protocol are not progressed satisfactorily in most of the countries. Considering such circumstances, international emissions trading (IET) will be a core method to efficiently abate greenhouse gases (GHG) emissions. Although a number of the related economic studies have been done, most of such studies assume the traditional economic theory such as the representative individual and the perfect rationality to avoid difficulties in the analysis. As a result, equilibrium solutions are introduced under such assumptions using top-down models with sophisticated mathematical formulae, in which some important and complex conditions of real economic systems are ignored. However, the real world which is based on interactions among economic entities and among economic entities and systems is extremely complex, and the behavior of economic entities is bounded rational. Furthermore, it is not always in the equilibrium state. Therefore, while traditional economic methodologies are easy to operate and useful to observe rough results of such complicated behavior, they are not enough to analyze social and economic problems in detail. In addition, there is possibility that misdirected outcomes are drawn.

In order to solve the problems of traditional economic methodologies, multi-agent simulation analysis, a bottom-up approach, is considered one of the useful approaches. It starts from micro-agents and they behave based on their own local information, namely bounded rationality of agents is considered. It can properly express the condition of social systems in which interactions among micro-agents and among micro-agents and macro-systems are observed. Recently, market analysis based on this approach is seen in some studies (Izumi (2003), Kaneda (2005)) and it is also applied to analyze IET (Mizuta and Yamagata (2001, 2003), Kimura and Oda (2002), Oda et al. (2003))[1]. However, the framework of this methodology has not been consolidated, yet, in spite of its availableness.

In this paper, a unique multi-agent model is constructed and IET considering the Kyoto Protocol is analyzed. Then, the results of the simulations are shown and compared with the states brought by the "theoretical IET", perfectly rational IET, and the "no IET", that is all regions achieve the emissions targets without IET.

As studies of artificial market applying multi-agent models can be classified into three categories, namely studies focusing on structure and learning of agents, market structural models, and interrelationships between micro-behavior of agents and macro-behavior of markets (Hamagami (2006)), this study corresponds to the third one. Although studies of artificial market using multi-agent models are useful as described, some issues such as difficulties to settle environment or conditions of market exactly and to model agents which are heterogeneous and changing continuously are also pointed out (Hamagami (2006)). Therefore, this study tries to solve the problems by referring to a part of previous studies.

2. Methods

2.1 Assumptions of Analysis

The assumptions of this analysis are as follows. Countries participating in IET are developed countries and economies in transition ratifying the Kyoto Protocol, and they are aggregated into 4 regions. That is to say, developed countries withdrawing from it, the United States and Australia, are not considered here. Each region is thought an independent agent. Then, only CO_2 emissions and IET of CO_2 are considered (not all of GHG) in the analysis. Because the Kyoto Protocol is taken into account, the target period is the first commitment period and the emissions targets of the regions follow it.

The BAU CO_2 emissions levels of the regions in years 2008-2012 are estimated referring to the latest emissions data of Marland et al. (2006) and the expected growth rates of CO_2 emissions from IEA (2004). Then, the emissions rights assigned to each region are calculated from the Kyoto Protocol.

Table 1 shows the assumptions described above. JPN, E_U, and KPI are developed countries, and EFS is economies in transition.

Table 1: Structure of Regions, Emissions Targets (% from base year), and Total BAU CO_2 Emissions and Total Emissions Rights for 5 years (Mt-CO_2)

Code	Region	Target	CO_2 Emissions	Emissions Rights
JPN	Japan	94	6685.4	5035.8
E_U	EU	92	17183.8	14349.7
KPI	Rest of the OECD countries included in the Annex B of the Kyoto Protocol and ratifying it	94.5	3760.8	2456.4
EFS	Russia and Eastern Europe included in the Annex B of the Kyoto Protocol and ratifying it	98.1	14118.8	19949.8

1 Multi-agent models are used to analyze various social and scientific phenomena. Studies about ecosystems, stock markets, traffic jams, political negotiations, and communications are the examples.

2.2 Multi-Agent Model

As described in the above section, there are some previous studies analyzing IET applying multi-agent models. Although Kimura and Oda (2002), Mizuta and Yamagata (2001, 2003), and Oda et al. (2003) give crucial hints to construct the model of this study, it also includes some unique and realistic characteristics. For example, unlike Kimura and Oda (2002) and Oda et al. (2003), marginal abatement cost (MAC) functions are adopted for decision making, whether to trade emissions rights or not, of each region[2]. Furthermore, real regions and their emissions rights and emissions are used instead of imaginary ones. Also, the constructed model can appropriately treat behavior of regions whose emissions rights are not less than the CO_2 emissions[3]. Then, unlike Mizuta and Yamagata (2001, 2003), bilateral trade is applied as the trade method[4] and trade is made multiple times in one year whenever an offer price, an expected trading price, to sell or to buy is accepted by a target region[5]. Moreover, each region uses strategies for decision making. The details of this model are described below.

In this model, the trade method adopted is bilateral trade as mentioned above[6] and the purpose of each region is to abate CO_2 emissions below its emissions rights and to minimize the cost (or to maximize the profit) simultaneously. Each region behaves based on the local information of its own such as the MAC function, the CO_2 emissions, the emissions rights, and the strategies.

The flow of the model is as follows. Also, Fig.1 shows the structure of trade in the model.

1. Establishment of the annual plan
   (once at the start of a year)
2. Offer to sell or buy, answer, and trade
   (repeated 365 times a year)
3. Self-abatement of CO_2 emissions
   (once in the year end)

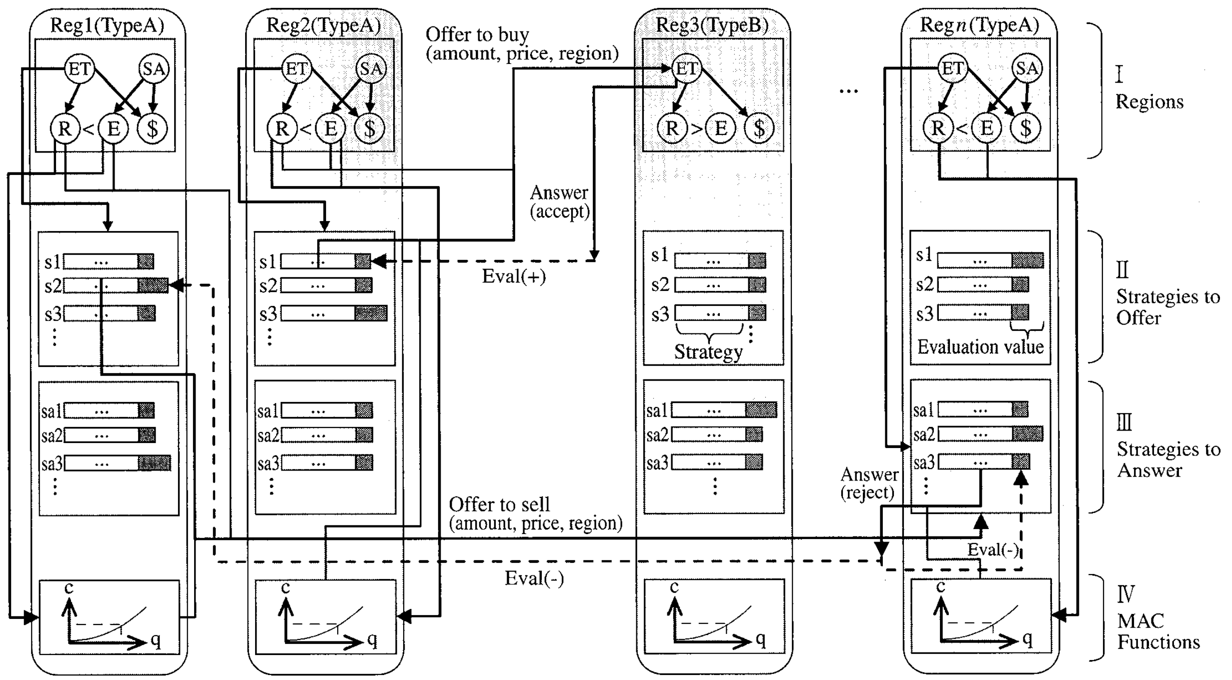

Fig. 1: Structure of Trade

* Reg: region, ET: emissions trading, SA: self-abatement, R: emissions rights, E: CO_2 emissions, $: money, s: strategy to offer, sa: strategy to answer, Eval(+): positive evaluation, Eval(-): negative evaluation, c: MAC, q: abatement level

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2 Kimura and Oda (2002) and Oda et al. (2003) consider that MAC of each region is constant.

3 EFS comes under this example.

4 Mizuta and Yamagata (2001, 2003) apply double auction as the trade method.

5 Mizuta and Yamagata (2001, 2003) assume that trade is made once a year under the equilibrium state.

6 Although some other trade methods such as double auction can be considered, bilateral trade is adopted because the number of traders is small in this study.

The first stage is a process to determine a CO_2 amount each region expects to abate and to trade in the year. There are two types of choices according to the CO_2 emissions and the emissions rights of each region (Fig. 1-I). If a region has the emissions rights less than the CO_2 emissions (Type A), it can be both a buyer and a seller of emissions rights. It determines the expected amount to abate by itself and through IET in the year based on its self-abatement rate[7], its deficient emissions rights, and remaining years. It also determines the expected amount of the emissions rights it is willing to sell and to buy where the amount to buy is thought to be larger than that to sell. If a region has the excess emissions rights (Type B), on the other hand, it only can be a seller and determines the expected amount it is willing to sell based on the excess amount and remaining years.

The second stage is a process to trade. Concerning Type A, each region selects a strategy to offer (Fig. 1-II), determines an offer amount (Fig. 1-I), which is an expected trading amount, and calculates MAC (Fig. 1-IV) to determine an offer price. Each strategy is composed of a position (2 options), which determines to be a buyer or a seller, a range of offer price (10 options), which determines how much to add on (to reduce from) MAC when offering to sell (to buy) in percentages 1-10%, and a target (3 options), which is to determine a trading partner. That is to say, each region has 60 (2 × 10 × 3) kinds of strategies[8]. In addition, an evaluation value, which indicates how superior the strategy is, is assigned to it and it is selected randomly with the probability proportional to the evaluation[9]. The offer amount is determined according to the expected buying or selling amount obtained in the first stage. The offer price to sell (to buy) is determined to be able to gain profit (to reduce cost) from trade and self-abatement. Therefore, the offer price to sell (to buy) is calculated by adding (reducing) the range of offer price obtained from the selected strategy on (from) the MAC. Then, information about the offer price and the offer amount is sent to the trading partner determined by the selected strategy. When a region of Type A receives an offer message, it determines whether to accept or to reject it by selecting a strategy to answer (Fig. 1-III). Each strategy is composed of a target (3 options), which is to determine a trading partner, and a range of price (10 options). That is to say, each region has 30 (3 × 10) kinds of strategies to answer[10]. If the offer price to buy (to sell) from the determined trading partner is higher (lower) than the MAC plus (minus) the range of price of the receiver, the offer message is accepted and the entire offer amount is traded. The offer price is treated as the trading price. On the contrary, the offer message is rejected if the offer price to buy (to sell) is lower (higher) than the MAC plus (minus) the range of price of the receiver.

Concerning Type B, they do not send any offer messages and only receive the messages. Because each region only can be a seller, it does not use strategies to determine the behavior and it accepts offers to buy and rejects offers to sell. The offer price is treated as the trading price and the entire offer amount is traded.

When a trade is made, the evaluation value on the selected strategy (both the strategy to offer and to answer) is updated. Since success of trade means success of the selected strategy, the evaluation on it is raised. On the contrary, since failure of trade means failure of the selected strategy, the evaluation on it is lowered. The evaluation is changed proportionally to the range of price. That is, the updated value is calculated by [original value ± range of price][11]. Because regions of Type B do not use strategies, this process is implemented only for regions of Type A.

The third stage is a process of self-abatement (Fig. 1-I). This model assumes that each region abates its CO_2 emissions over its emissions rights by itself as a result of IET and it is implemented every year. Although the self-abatement amount is determined according to the self-abatement rate, the rate is updated every year and the CO_2 emissions become equal to the emissions rights in each region in the final year[12].

The model is constructed using a simulator, KK-MAS, developed by KOZO KEIKAKU ENGINEERING Inc..

2.3 Marginal Abatement Cost Functions

As described above, MAC functions are used to calculate MAC. They are estimated using a general equilibrium model, the GTAP-E model (Burniaux and Truong (2002)). Each of them is a function of the abatement levels and each region has

7 The rates are set 0.9 for all regions.

8 The strategies to offer are same for all regions.

9 The initial values are 100 for all strategies.

10 The strategies to answer are also same for all regions.

11 This way of selection and learning is called reinforcement learning, a kind of rule learning (Brenner (2006)).

12 However, there is possibility that emissions rights are larger than CO_2 emissions.

a unique function. In order to construct each one, the GTAP-E model is run under different abatement levels of the corresponding region[13] and MAC against each abatement level is obtained. Then, a MAC function (a quadratic function: $c = aq^2 + bq$, where c is the MAC in \$/t-CO_2, q is the abatement level in Mt-CO_2, and a and b are the coefficients) of each region is approximated by the least squares method. Table 2 shows the coefficients, a and b. All coefficients of determination in the approximations are 0.99. In this study, identical MAC functions are applied every year to make the analysis simple.

Table 2: Coefficients of Estimated MAC Functions ($c = aq^2 + bq$)

Region	*a*	*b*
JPN	2.3×10^{-4}	1.2×10^{-1}
E_U	2.4×10^{-5}	3.6×10^{-2}
KPI	3.6×10^{-4}	1.1×10^{-1}
EFS	2.1×10^{-5}	3.0×10^{-2}

3. Results and Discussions

For the analysis, the above multi-agent simulation model is run for 50 times[14]. In this section, at first, the results of the simulations are shown and then, they are compared with the calculated results of the no IET and the theoretical IET.

The results are summarized in Table 3 and Table 4. Also, Fig. 2 shows one simulation result.

Table 3: Summary of Simulation Results (Trade)

	Value
Average Price (\$/t-CO_2)	26.66 (0.36)
Traded Amount (Mt-CO_2/y)	468.56 (8.38)
Annual Trade Frequency	278.86 (3.47)

*The values are averages and standard deviations.

Table 4: Summary of Simulation Results (Regional Influences)

Region	Cost (M\$/y)	Self-Abatement (Mt-CO_2/y)
JPN	7819.67 (47.86)	185.49 (1.89)
E_U	6272.20 (53.93)	430.27 (5.70)
KPI	4931.88 (30.21)	160.582 (1.70)
EFS	-9328.99 (86.49)	0 (0)
Total	9694.77 (153.24)	3881.42 (45.46)

*The values are averages and standard deviations.

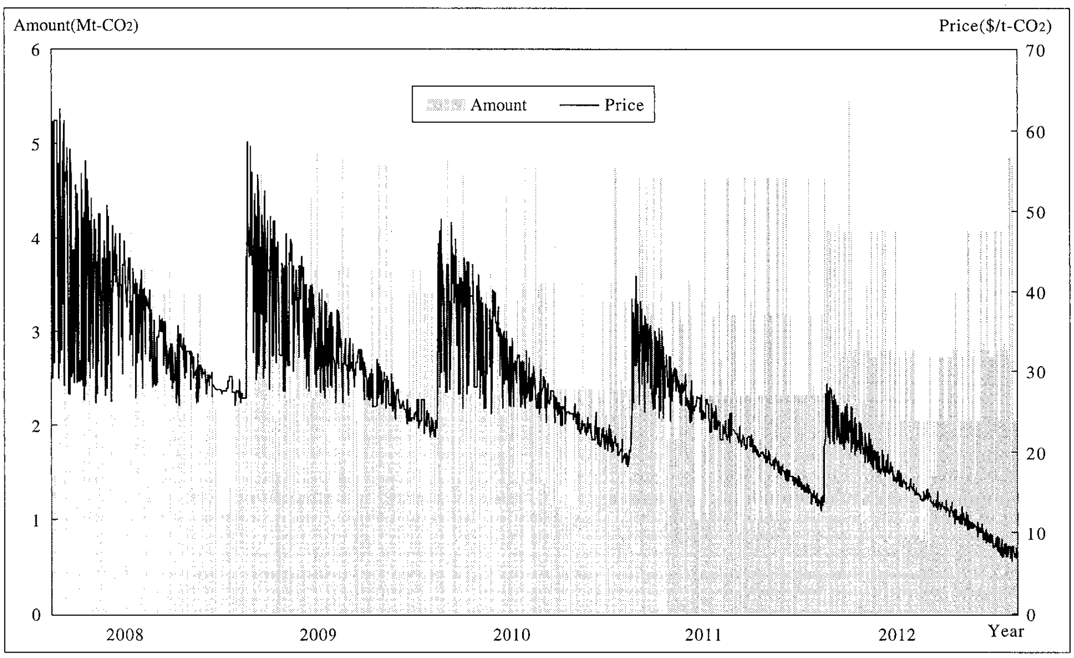

Fig. 2: One Simulation Result

13 In this study, 1%, 5%, 10%, 15%, 20%, 25%, and 30% abatement of the CO_2 emissions are used to estimate.

14 Because some variables such as offer prices and offer amounts take random values in each trial and different results are brought consequently, the simulation is implemented 50 times to obtain the average of the trials.

On the whole, as Table 3 and Table 4 indicate, no big differences are seen among the trials. Standard deviations shown in the tables are relatively small. However, as Fig. 2 represents, trading prices and trading amounts fluctuate widely in each simulation. In this case, trade is implemented 1394 times in 5 years. The average price is \$26.34/t-CO_2, whereas the standard deviation is \$10.18/t-CO_2 (the highest one is \$64.68/t-CO_2 and the lowest one is \$6.51/t-CO_2), and the average trading amount in one time is 1.74Mt-CO_2, whereas the standard deviation is 1.02Mt-CO_2 (the largest one is 5.46Mt-CO_2 and the smallest one is zero). The trading price tends to decrease in each year and year by year[15, 16], and the trading amount tends to increase year by year[17]. The cause of the first tendency is that the more the cumulative purchase amount of emissions rights of each region in a year, the lower the demand price, namely the offer price to buy. The cause of the second tendency is that because the regions which hold insufficient amount of emissions rights tend to demand more emissions rights as years pass to achieve the targets and one region, EFS, holds sufficient amount of emissions rights to sell, the average demand price is decreased. Then, the cause of the third tendency is that because the average price is declined year by year, the demand is increased in later years. Concerning the trade frequency, as trade is realized 75%, it is due to the continual behavior of EFS as a seller.

Concerning the influences on each region, it costs the developed countries to achieve the targets. On the other hand, because EFS holds a large amount of excess emissions rights, it gains some profit through IET and abates no CO_2 emissions by itself at all.

Next, comparisons of the above results with the no IET and the theoretical IET show some interesting results. The latter two are calculated from the MAC functions and the calculated results are shown in Table 5. Concerning the no IET, each self-abatement amount is [(emissions – emissions rights) / 5] of the region[18] and each cost is calculated by $[\int(aq_i^2 + bq_i)\, dq_i]$ where q_i is the self-abatement amount of region i. Concerning the theoretical IET, because the total emissions rights are larger than the total CO_2 emissions[19] in the world, the costs and the self-abatement amounts of each region and the world are zero. In this case, the trading price is zero as well.

Table 5: Calculated Results of No IET and Theoretical IET

Region	No IET		Theoretical IET	
	Cost (M\$/y)	Self-Abatement ($Mt\text{-}CO_2/y$)	Cost (M\$/y)	Self-Abatement ($Mt\text{-}CO_2/y$)
JPN	9527.33	329.92	0	0
E_U	7285.72	566.81	0	0
KPI	5815.69	260.88	0	0
EFS	0	0	0	0
Total	22628.74	1157.61	0	0

Comparing the simulation results with the no IET, the costs and the self-abatement amounts of the developed countries are smaller, and EFS gains some profit through IET. Consequently, the total cost is smaller as well. Comparing with the theoretical IET, on the other hand, the costs and the self-abatement amounts of the developed countries are larger. Also, the trading price is higher. However, EFS gains profits because it does not sell the entire amount it can sell and the trading price becomes much higher as a result. Consequently, the total cost becomes larger as well. The reasons that the simulation results are inferior are as follows. Concerning the theoretical IET, since trade is implemented

15 The average trading price is \$36.84/t-CO_2 in the first year, \$32.47/t-CO_2 in the second year, \$28.83/t-CO_2 in the third year, \$23.05/t-CO_2 in the fourth year, and \$15.65/t-CO_2 in the final year.

16 These tendencies are true for the other simulation results.

17 The trading amount is 373.74Mt-CO_2 in the first year, 473.30Mt-CO_2 in the second year, 460.96Mt-CO_2 in the third year, 529.69Mt-CO_2 in the fourth year, and 582.14Mt-CO_2 in the final year.

18 If the solution is below zero, it means that the region does not abate emissions.

19 The total amounts of emissions rights and CO_2 emissions are the sum of emissions rights and CO_2 emissions of the 4 regions, respectively.

to equalize MAC of all regions by the top-down approach, one exactly optimum trading price is determined and just a optimum quantity of emissions rights are traded. With regard to the simulation, however, regions take the initiative of the trade and they never know the overall optimality. In addition, trade is implemented repeatedly in a year, and trading price and amount fluctuate depending on market conditions (see Fig. 2). Consequently, the optimum trade is not realized unlike the theoretical IET.

From these comparisons, it is indicated that the simulation results are placed between the no IET and the theoretical IET, and the actual cost reduction effects brought by IET are much smaller than the theoretical expectation.

4. Concluding Remarks

In this study, a multi-agent model for analysis of emissions trading was structured and IET was simulated. Then, by comparing the simulation results with the "no IET" and the "theoretical IET", the effects of IET under the condition of bounded rationality were clarified. As a result, because emissions rights were sold to developed countries, the total cost to achieve the targets of the Kyoto Protocol was reduced through IET even under bounded rationality of regions (agents). However, the realized efficiency was far below that brought by the theoretical IET, in spite of the vigorous trade.

This study has a significant meaning that it is proved numerically by virtue of simulation analysis that IET implemented by bounded rational agents, which is a more realistic assumption than traditional analytical methods, does not bring the theoretical cost-efficiency but contributes to cost-efficiency to some extent. Then, since theoretical IET never exists in reality, it is expected that this study and the constructed model will help analyzing and finding effective and efficient IET systems reflecting reality.

Regarding the relations of the result of this study with the emissions trading under the Kyoto Protocol, while it has not been started yet, it is anticipated that the effect will be much smaller than the expected effect insisted in the theory. Therefore, when emissions trading under the Kyoto Protocol is actually started, it is necessary to be cautious of the problem, and to make a decision and to behave by taking into account it.

For the future investigation, it is important to analyze the influences when different trade methods are adopted and when the number of regions participating in IET is different, and to compare with those results. In addition, because the constructed model was a simple framework and only IET under simple assumptions was analyzed, it is necessary to study methods to analyze IET by incorporating some realistic assumptions such as trading costs, administrative costs, and influences of various related policies into the model. Furthermore, investigation of more efficient IET is necessary as well.

References

Brenner, T. (2006) Agent Learning Representation: Advice on Modelling Economic Learning. In Tesfatsion, L. and Judd, K.L. (eds.) Handbook of Computational Economics: Agent-based Computational Economics. Elsevier: Amsterdam, 895-947.

Burniaux, J.M. and Truong, T.P. (2002) GTAP-E: An Energy-Environmental Version of the GTAP Model. GTAP Technical Paper 16.

Hamagami, T. (2006) Using Intelligent System Approaches for Simulation of Electricity Markets. IEEJ Trans. EIS 126(2), 156-160 (in Japanese).

IEA (2004) World Energy Outlook 2004. IEA Publications: Paris.

Izumi, K. (2003) Artificial Market. Morikita Publishing: Tokyo (in Japanese).

Kaneda, T. (2005) Simulation & Gaming of the Social Design. Kyoritsu shuppan: Tokyo (in Japanese).

Kimura, K. and Oda, M. (2002) Formation of the International Environmental Regime-Searching for Desirable Emissions Trading System. In Yamakage, S. and Hattori, S (eds.) Artificial Society in the Computer. Kyoritsu Shuppan: Tokyo, 195-210 (in Japanese).

Marland, G., Boden, T.A., and Andres R.J. (2006) Global, Regional, and National Fossil Fuel CO_2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A., http://cdiac.ornl.gov/. Cited December 4, 2006.

Mizuta, H. and Yamagata, Y. (2001) Agent-based Simulation and Greenhouse Gas Emissions Trading. Proceedings of the 2001 Winter Simulation Conference, 535-540.

Mizuta, H. and Yamagata, Y. (2002) Simulation and Gaming for International Emissions Trading IEICE Technical Report 101(536), 65-71 (in Japanese).

Oda, M., Kimura, K., and Tamada, M. (2003) A Study of International Emissions Trading Using Multi-Agent Simulation. IEICE Technical Report 102(613), 43-46 (in Japanese).