Regional and Sectoral Impacts of Climate Change under International Climate Agreements

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Abstract

This article examines regional and sectoral impacts of climate change under international climate agreements for abating GHGs. Using the dynamic Evaluation Model for Environmental Damage and Adaption (EMEDA), it examines interactions and heterogeneity among various countries. Specifically, we define a sub-global CO2 abatement game involving players from three regions (Japan, China and the U.S.). Simulated results show that: 1) in each scenario, overall costs of impacts in developed countries are less than those in developing nations, some of which lose more than 10% of their real GDPs; 2) an extra 0.8 degrees C temperature rise occurs in 2100 with China and the U.S. deviating from the scenario proposed by international society. This leads to increased climate damages in other developed countries by over 1% of real GDP; and 3) positive sectoral impacts can be found in several regions such as Japan, China, the U.S., EU, FSU and Africa.

JEL-Classification: C68, C70, Q54
Keywords: EMEDA; integrated assessment model; IAMs; CGE models; global warming; climate change; non-cooperative game; bargaining game; Nash equilibrium; Nash bargaining solution.

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1. Introduction

The continued rising of anthropogenic greenhouse gas (GHG) emissions and the worsening climate crisis have been attracting mounting attention for the last several decades. The Kyoto Protocol for mitigating global warming was adopted at the 3rd Conference of the Parties (COP3) of the United Nations Framework Convention on Climate Change (UNFCCC) in 1997. Although international society has been facing many challenges regarding the implementation of required GHG reductions, the agreement in Kyoto nevertheless requires developed countries (Annex I parties under the Kyoto Protocol) to reduce emissions during the period of 2008 to 2012. However, in 2001, the Bush Administration of the United States (U.S.) rejected the protocol stating at that time that 1) emissions targets embodied in the Kyoto Protocol were arbitrary and not based upon science, and 2) no one could say with any certainty what constitutes a dangerous level of warming for humanity, and therefore, what level must be avoided (O'Neill and Oppenheimer, 2002). In addition to this failure to secure the participation of the U.S., China's carbon dioxide (CO2) emissions have rapidly increased with the dramatic expansion of the Chinese economy this century. The total amount of CO2 emissions for this country are now by far the largest in the world, even though China still belongs to the developing country (Annex II parties under the Kyoto Protocol) group with no binding commitments required under the Kyoto Protocol. Furthermore, after ratification of the protocol, the Japanese government stated at COP17 in 2011 that it was not willing to participate in an extension of the treaty. With such factors harboring the potential to significantly accelerate global warming and associated climate change, more and more emphasis across the world is being given to cooperation among these countries in the goal of attaining sustainable economic growth.

Since the early nineties many scholars have developed integrated assessment models (IAMs) in the goal of simulating the impacts of climate change (e.g., Frankhauser, 1995; Nordhaus and Boyer, 2000; Nordhaus, 1991; Nordhaus and Yang, 1996; Tol, 1995, 1999, 2002). In the literature (e.g., Nakicenovic and Swart, 2000), most GHG emission scenarios are based on those from the Intergovernmental Panel on Climate Change (IPCC) and are calculated with IAMs aiming to maximize world welfare. On the other hand, Stern (2007) points out that the literature does not measure 'second-round' socio-economic responses to the impacts of climate change such as conflict and migration. When each region maximizes its own objective function—and not world social welfare—actual CO2 emissions of each region may deviate from mitigation targets determined by international society. This subsequent increase in GHG emissions has the potential to trigger more severe climate change impacts than those predicted. Therefore, it is necessary to construct a new scenario in which each region chooses the level of its CO2 emissions strategically, and then compare this with another scenario where CO2 emissions reduction targets are determined by the international community.

Several scholars have recently analyzed the CO2 abatements attained by climate policies among regions using both IAMs and game theoretical models. For instance, Babiker (2001) builds repeated games of CO2 abatement using a static 26-region and 13-commodity computable general equilibrium (CGE) framework. This is conducted to study the economic incentives and institutional issues governing the outcomes of a short-term climate change policy package by the UNFCCC and the Berlin Mandate initiatives. Their study demonstrates that the achievement of a coalition among OECD regions might require the design of suitable trade instruments. Eyckmans and Tulkens (2003) simulate cooperative game theoretic aspects of global climate negotiations using a CLIMNEG world simulation (CWS) model derived from a RICE model by Nordhaus and Yang (1996). They state the necessary conditions for CWS that determine Pareto efficient investment and emission abatement paths under alternative regimes of cooperation among the regions. Finally, Yang (2003) implements a new algorithm in a RICE model to develop a feasible modeling approach applying closed-loop strategies to study the issues of reevaluation and renegotiation of climate change coalitions.

However, there are limitations to this literature. Few studies have focused on regional and sectoral impacts of climate change derived from the non-cooperative and bargaining behaviors for CO2 abatement among various countries. Also, few of them have employed multi-sector dynamic IAMs for analyzing strategic behaviors for CO2 emissions and their associated economic impacts, which typically vary across sectors. Attempting to address these deficiencies in the literature, in this paper we use a dynamic version of the Evaluation Model for Environmental Damage and Adaption (EMEDA), developed by Washida et al. (2013b). Concentrating on the period 2004-2100, our goal is to investigate various consequences of global warming such as climate impacts and abatement costs by considering both cooperative and non-cooperative behaviors under multilateral negotiations on the mitigation of CO2 emissions. This study extends a dynamic EMEDA to simulate the world economy as eight regions with each region broken down further into eight sectors. To calculate annually the recursive competitive equilibrium, we have utilized the GTAP7 Data Base and the General Algebraic Modeling System (GAMS) software[1]. Additionally, we have added global warming and damage functions modified from DICE2010 and RICE2010 (Nordhaus, 2012).

To formulate global climate negotiations, we define new CO2 abatement games where i) a set of players is formed by either *China* and *the U.S.*, or the three regions of *Japan*, *China* and *the U.S.*, ii) players' strategy spaces are determined by the rate at which CO2 emissions are reduced, and iii) payoff functions are calculated by the sum of discounted utilities calculated by a dynamic EMEDA. In this study, the CO2 emissions reduction rates in other regions not participating in the game are fixed. In a first game, we use a Nash equilibrium (N.E.) (Nash, 1950a, 1951) where each player behaves non-cooperatively. We then run a bargaining game with a Nash bargaining solution (N.B.S.) (Nash, 1950b) where the disagreement point is determined by the Nash equilibrium. This bargaining solution represents the cooperative outcome of negotiations among all players. Finally, to compare scenarios we measure regional and sectoral impacts of climate change when specific regions either behave cooperatively or in self-interest. Specifically, we calculate competitive equilibria in several scenarios, including the Nash equilibrium and the Nash bargaining solution for our games. Comparing these equilibria with an equilibrium in the

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[1] http://www.gams.com/

benchmark scenario (where no region suffers climate damage) we obtain economic losses for each region and loss in real value-added for each sector in terms of real Gross Domestic Product (GDP)[2].

Simulated results from the CO2 abatement games indicate that: 1) each player chooses a lower rate of reduction for CO2 emissions at the Nash equilibrium than at the Nash bargaining solution; 2) simulated CO2 emissions under the reduction rates from the solutions emerging from both games are higher than official reduction pledges made by three countries; 3) an increase in the rate of time preference causes a decrease in the rate at which CO2 emissions are reduced; 4) overall economic impacts in the developed countries are less than those in the developing countries, some of which lose more than 10% of their real GDPs in each scenario; 5) an extra 0.8°C temperature rise occurs in 2100 with China and the U.S. deviating from the scenario proposed by the international community. This leads to increased climate damages to the other developed countries, by more than 1% of real GDP; 6) for the secondary industry, the real value-added losses of both China and the U.S. are improved in the scenarios derived from game solutions, even if real GDP loss in China is worsened; and 7) positive sectoral impacts can be found in several regions such as Japan, China, the U.S., European Union (EU), former Soviet Union (FSU) and Africa.

This paper is organized as follows. Section 2 describes a dynamic EMEDA structure and our CO2 emission scenarios. The CO2 abatement game and bargaining CO2 abatement games are defined in section 3, with section 4 presenting results of the dynamic EMEDA games. Section 5 illustrates regional and sectoral impacts of climate change. The last section then provides concluding remarks.

2. Methodology

With much scholarship providing assessments of the global and regional economic impacts of climate change, some focus on economic consequences from multiple sectors and regions. In this study, we use a dynamic EMEDA developed by Washida et al. (2013b). This model builds upon the previous work (Washida, 2010; Washida et al., 2013a), which we employ a static CGE model for simulating economic impacts resulting from global warming and adaptation costs.

2.1. Extension to dynamic EMEDA

In this study, we employ a dynamic EMEDA in which a competitive equilibrium is recursively calculated year by year from 2004 to 2100[3]. As can be seen from Table 1, 2 and 3[4], we simulate the world economy as eight regions, with each region broken down into a

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[2] This is a comparative static approach, adopted for calculating economic impacts of climate change. See for example Eboli et al. (2010) and Washida et al. (2013).

[3] Since data in GTAP7 is available for 2004, this has been set as the base year by Washida (2010).

[4] Sector codes in Table 3 are available on the GTAP website https://www.gtap.agecon.purdue.edu/databases/v7/v7_sectors.asp.

	Regions		Sectors
1	Japan	1	Agriculture
2	China	2	Forestry
3	USA	3	Fishing
4	EU25_WEurope	4	Extraction
5	FSU_EEurope	5	LightMnfc
6	OAsiaOceania	6	HeavyMnfc
7	OAmerica	7	TransComm
8	Africa	8	OthServices

Table 1: Regions and Sectors for Dynamic EMEDA

Abb.	Name	Country codes (GTAP7)
1	Japan	JPN
2	China	CHN, HKG
3	USA	USA
4	EU25_ WEurope	AUT, BEL, CYP, CZE, DNK, EST, FIN, FRA, DEU, GRC, HUN, IRL, ITA, LVA, LTU, LUX, MLT, NLD, POL, PRT, SVK, SVN, ESP, SWE, GBR, XEF, NOR, CHE
5	FSU_ EEurope	RUS, ALB, BGR, BLR, HRV, ROU, UKR, XEE, XER, KAZ, KGZ, XSU, ARM, AZE, GEO
6	OAsiaOceania	IND, KOR, AUS, NZL, XOC, TWN, XEA, KHM, IDN, LAO, MMR, MYS, PHL, SGP, THA, VNM, XSE, BGD, PAK, LKA, XSA, IRN, TUR, XWS
7	OAmerica	CAN, MEX, XNA, ARG, BOL, BRA, CHL, COL, ECU, PRY, PER, URY, VEN, XSM, CRI, GTM, NIC, PAN, XCA, XCB
8	Africa	NGA, SEN, XWF, XCF, XAC, ETH, MDG, MWI, MUS, MOZ, TZA, UGA, ZMB, ZWE, XEC, BWA, ZAF, XSC, EGY, MAR, TUN, XNF

Table 2: Regions Considered in Dynamic EMEDA

Abb.	Name	Sector codes (GTAP7)
1	Agriculture	PDR, WHT, GRO, PCR, V_F, OSD, C_B, PFB, OCR, CTL, OAP, RMK, WOL, CMT, OMT
2	Forestry	FRS
3	Fishing	FSH
4	Extraction	COA, OIL, GAS, OMN
5	LightMnfc	VOL, MIL, SGR, OFD, B_T, TEX, WAP, LEA, LUM, PPP, FMP, MVH, OTN, OMF
6	HeavyMnfc	P_C, CRP, NMM, I_S, NFM, ELE, OME, ELY, GDT, WTR, CNS
7	TransComm	TRD, OTP, WTP, ATP, CMN
8	OthServices	OFI, ISR, OBS, ROS, OSG, DWE

Table 3: Sectors Considered in Dynamic EMEDA

further eight sectors.

In this paper, we have sought to improve a dynamic EMEDA on five levels from EMEDA (Washida, 2010). First, we adopt capital accumulation by sector in each region[5]. Second, we introduce population growth into labor supply[6]. Third, we introduce the Hicks-neutral technological progress into the value-added production function[7]. Fourth, we consider CO2 emissions derived from production[8]. Finally, we build a global warming model modified from DICE2010 and RICE2010 (Nordhaus, 2010, 2012)[9].

2.2. A CO2 emissions reduction scenario

In this subsection, we define a series of scenarios depicting various reduction rates for world CO2 emissions. In the base scenario, each region gradually increases the rate of CO2 emissions reductions according to Table 4. In this table, CO2 emissions and reduction targets in the year 2020 for the five major regions of Japan, China, the U.S., EU and FSU are derived from those officially announced at COP15 (den Elzen et al., 2010). For the other three regions, other Asia and Oceania (OAsiaOceania), other American countries (OAmerica) and Africa, for simplification purposes we have adopted 40% below 2005 levels. For long-term CO2 emissions reduction targets in the year 2050, we have followed targets set out by the International Energy Agency (IEA) and the Group of Eight (G8), which predict reduction rates for CO2 emissions in 2050 as 50% below 1990 levels (IEA, 2009; G8 Summit, 2007). For Japan, however, we have adopted an 80% reduction target since this country officially pledged such reductions by the year 2050 (METI, 2010). Moreover, for China, we have adopted 50% below 2005 levels since CO2 reduction rates of China in 2050 is higher than other regions. Finally, we assume that each region reduces its CO2 emissions after 2050 at a rate of 2% per annum. Annual change in CO2 reduction rates of each region in the base scenario is illustrated by Figure 1.

Figure 2 represents change in atmospheric temperature in both the base scenario and the no-reduction scenario where no region reduces CO2 emissions. In a dynamic EMEDA, the temperature rise in 2100 emerges as approximately 2.31°C relative to the year 1900 in the base scenario and 4.43°C in the no-reduction scenario. Therefore, it can be seen that attaining the base scenario is sufficient for limiting global warming as per the current goal

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[5] In each period a present capital stock is the sum of the previous capital stock minus depreciation of the previous capital stock plus a previous gross investment. We set the depreciation rate of each sector to four percent per annum following the GTAP7 database.

[6] Population growth rates are calculated by world projections from the United Nations (UN) data.

[7] The growth rates of technological progress are calculated by fitting the estimated values of real GDP in a dynamic EMEDA to those of real GDP in the scenario of Shared Socio-economic Pathways (SSP). In this scenario, both potential damage of global warming and marginal cost of mitigation are low (SSP1), which is in turn estimated by the OECD ENV-linkage model (SSP Database, 2012).

[8] CO2 emissions in 2004 are calculated by input energy data in the GTAP7 Data Base (Lee, 2008). Effects of non-CO2 GHGs are given exogenously according to DICE2010 (Nordhaus, 2012). Technology progress in abatement is calculated according to RICE2010 (Nordhaus, 2010, 2012).

[9] The global warming model consists of equations on radiative forcing and climate change, sea level rise (SLR) and non-SLR damage functions, and abatement cost functions. The damage function is determined in accord with temperature rise and SLR with the abatement cost function for each region also being an increasing function of reduction rates for CO2 emissions.

Region	2020	2050	2051-2100
Japan	-25% below ’90	-80% below ’90	-2% p.a.
China	-40% below ’05[a]	-50% below ’05	-2% p.a.
USA	-4% below ’90	-50% below ’90	-2% p.a.
EU25_WEurope	-20% below ’90	-50% below ’90	-2% p.a.
FSU_EEurope	-20% below ’90	-50% below ’90	-2% p.a.
Oasia Oceania	-40% below ’05	-50% below ’90	-2% p.a.
OAmerica	-40% below ’05	-50% below ’90	-2% p.a.
Africa	-40% below ’05	-50% below ’90	-2% p.a.

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[a] Comparison by CO2 emissions intensity.

Table 4: CO2 Emissions Reduction in the Base Scenario

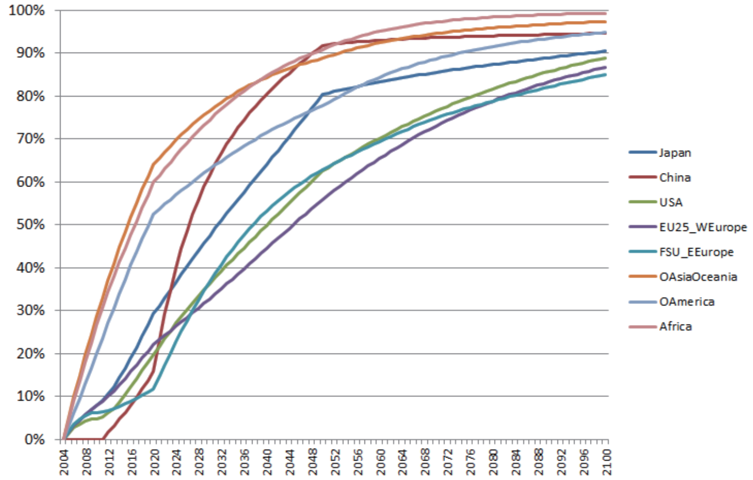

Figure 1: Change in Reduction Rates of Regional CO2 Emissions in the Base Scenario

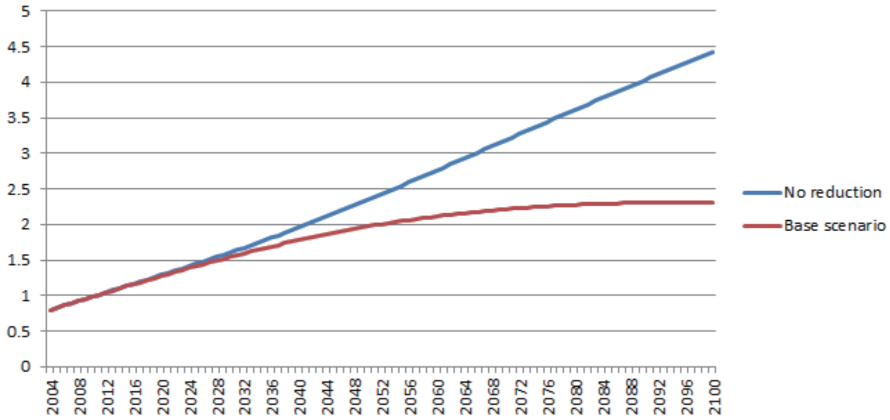

Figure 2: Change in Temperature (°C above 1900) in the Base Scenario and the No-Reduction Scenario

of 2.0-2.4°C in 2100 relative to pre-industrial temperatures[10].

3. Game analyses

In this section, we concentrate on the three players of Japan, China and the U.S. All of these three countries are characterized by unwillingness to participating in a post-Kyoto Protocol in spite of the fact that they collectively account for approximately half of world CO2 emissions. First, we define a CO2 abatement game and a Nash equilibrium. We then explore a bargaining CO2 abatement game and a Nash bargaining solution. Finally, we calculate these solutions using both the games and a dynamic EMEDA.

3.1. Nash equilibria for a CO2 abatement game

This sub-section provides an overview of the one-shot and non-cooperative game among regions, now referred to as a *CO2 abatement game*. The game is defined by (N, S, u). A set of players is N, defined as a subset of $\{Japan, China, USA\}$. $S = \prod_{r \in N} S_r$ is strategy space where each player r in N has their strategy space S_r. Payoff function is $u = (u_r)_{r \in N}$ where the payoff function for each player r is

$$u_r = \sum_{t=2004}^{2100} \frac{1}{(1+\rho)^{t-2004}} u_{r,t} \tag{1}$$

where u_r represents the sum of discounted utilities of player r when the rate of time preference is ρ. In this paper ρ is 1%, 3%, 5% or 10%. $u_{r,t}$ represents the utility of region r in period t, which is defined as

$$u_{r,t} = \left\{ \phi_r^C C_{r,t}^{\frac{\zeta_r - 1}{\zeta_r}} + \phi_r^S S_{r,t}^{\frac{\zeta_r - 1}{\zeta_r}} + \phi_r^G G_{r,t}^{\frac{\zeta_r - 1}{\zeta_r}} \right\}^{\frac{\zeta_r}{\zeta_r - 1}} \tag{2}$$

where $C_{r,t}$ is consumption, $S_{r,t}$ is savings, which is equivalent to gross investment, and $G_{r,t}$ is government expenditures[11].

One example is that of a case where each of China and the U.S. chooses specific strategies regarding reduction rates for CO2 emissions. The set of players is $N = \{China, USA\}$. We assume that S_r consists of eleven strategies of CO2 reduction rates $\mu_r = (\mu_{r,t})_{t=2004}^{2100}$. Each region's strategy consists of CO2 emissions reduction rates for that region, running from the period 2004 through to 2100. We have calculated strategies in accord with reduction rates, which are compared to CO2 emissions in the base scenario $\mu' = (\mu'_r)_{r \in N} = ((\mu'_{r,t})_{t=2004}^{2100})_{r \in N}$. Therefore, the strategy space for each player r, $S_r = \{\mu_r(0), \ldots, \mu_r(10)\}$, is given in Table 5[12]. Note that CO2 emissions reduction rates

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[10] This range derives from stabilization scenarios under Category I (IPCC, 2007).

[11] In the tables and figures of this paper, for simplicity we normalize the payoff to zero obtained when each player chooses no CO2 reduction.

[12] In this paper we refrain from adopting the base scenario μ' as a strategy because each region always chooses a lower reduction rate than that of strategy 1 in the game. Therefore each region can choose a strategy of higher reduction rates than that of strategy 1. See Appendix B for details.

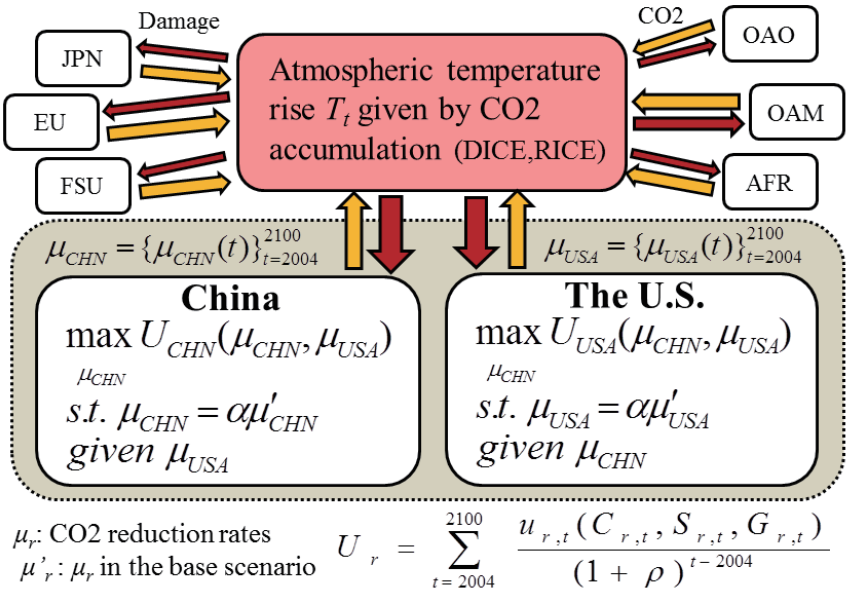

Figure 3: Description of the Two-Player CO2 Abatement Game

in other regions not participating in the game are fixed at those in the base scenario. Figure 3 depicts the relationship between the two players and the other six regions in a two-player CO2 abatement game.

In the same vein, we have also considered the case of three regions participating in a three-player game with the set of players defined as $N = \{Japan, China, USA\}$. Here we assume that each player has six strategies, provided in Table 6. For payoff functions in equation (1), we adopt the same function as that from the two-player game.

Next, we define a Nash equilibrium (Nash, 1950a, 1951) in our CO2 abatement game. A strategy profile may be considered a *Nash equilibrium* if each player's strategic choice is the best response to the strategies taken by the other players. Formally, a Nash equilibrium $s^* = (s_r^*)_{r \in N}$ in S satisfies $u_r(s_r^*, s_{-r}^*) \geq u_r(s_r, s_{-r}^*)$ for all r in N and s_r in S_r where $(s_r, s_{-r}) = s$ and $s_{-r} = (s_{r'})_{r' \in N \setminus \{r\}}$. That is to say, no player prefers to change her strategies at a Nash equilibrium. In the case of the two-player game, both China and the U.S. have no incentive to change CO2 reduction rates at a Nash equilibrium. A Nash equilibrium therefore can be regarded as a non-cooperative solution since each player acts in self-interest to maximize individual payoffs.

It should be pointed out incidentally that a Nash equilibrium is not always unique, as in some games multiple Nash equilibria may exist. Furthermore, a Nash equilibrium for other games maybe empty[13].

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[13] This holds in the case of pure strategies. Nash (1950a) demonstrates that a Nash equilibrium exists even in the case of mixed strategies.

Strategy	China	USA
0	0	0
1	$2.5\%\mu'_{China}$	$5\%\mu'_{USA}$
2	$5\%\mu'_{China}$	$10\%\mu'_{USA}$
3	$7.5\%\mu'_{China}$	$15\%\mu'_{USA}$
4	$10\%\mu'_{China}$	$20\%\mu'_{USA}$
5	$12.5\%\mu'_{China}$	$25\%\mu'_{USA}$
6	$15\%\mu'_{China}$	$30\%\mu'_{USA}$
7	$17.5\%\mu'_{China}$	$35\%\mu'_{USA}$
8	$20\%\mu'_{China}$	$40\%\mu'_{USA}$
9	$22.5\%\mu'_{China}$	$45\%\mu'_{USA}$
10	$25\%\mu'_{China}$	$50\%\mu'_{USA}$

Table 5: Strategies of China and the U.S. in the Two-Player Game

Strategy	Japan	China	USA
0	0	0	0
1	$5\%\mu'_{Japan}$	$5\%\mu'_{China}$	$10\%\mu'_{USA}$
2	$10\%\mu'_{Japan}$	$10\%\mu'_{China}$	$20\%\mu'_{USA}$
3	$15\%\mu'_{Japan}$	$15\%\mu'_{China}$	$30\%\mu'_{USA}$
4	$20\%\mu'_{Japan}$	$20\%\mu'_{China}$	$40\%\mu'_{USA}$
5	$25\%\mu'_{Japan}$	$25\%\mu'_{China}$	$50\%\mu'_{USA}$

Table 6: Strategies of Japan, China and the U.S. in the Three-Player Game

3.2. Nash bargaining solutions for a bargaining CO2 abatement game

In this subsection, we consider a case where players negotiate with each other, using the notations N, S and u, already defined in the previous subsection.

Here the *bargaining CO2 abatement game* consists of (N, F, d), with N again being the set of players. A feasibility set F is defined as

$$F = \{(\bar{u}_r)_{r\in N} \in \mathbf{R}^N | u_r((s_r)_{r\in N}) = \bar{u}_r,\ {}^{\exists}s_r \in S_r,\ {}^{\forall}r \in N\} \tag{3}$$

where s_r is a player r's strategy in S_r. This set consists of points representing the tuples of feasible payoffs by negotiation among players. The disagreement point will be set as $d = (d_r)_{r\in N}$ in $\mathbf{R}^N$, with the value of d given. A bargaining domain B is defined as

$$B = \{(b_r)_{r\in N} \in F | b_r \geq d_r\}. \tag{4}$$

With B evidentially a subset of F, for each player a point of B is always better than or equal to the disagreement point d. A point $(\bar{b}_r)_{r\in N}$ in B is a *Nash bargaining solution* (Nash, 1950b) if the following axioms are satisfied: (i) Pareto optimality; (ii) symmetry;

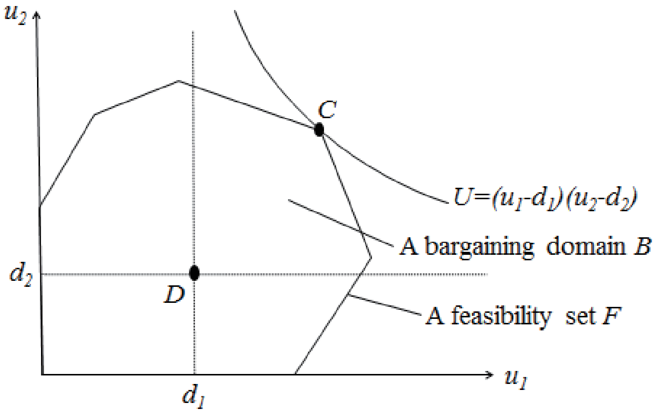

Figure 4: A Nash Bargaining Solution Between Two Players

(iii) scale invariance; and (iv) independence of irrelevant alternatives[14].

It is known that a Nash bargaining solution emerges as a result of the following maximization problem (Nash, 1950b)

$$\max_{(\bar{u}_r)_{r\in N}\in B} \prod_{r\in N} (\bar{u}_r - d_r). \tag{5}$$

Figure 4 shows a Nash bargaining solution at point C in the case of two players, 1 and 2. D is a disagreement point, with the curve representing the objective function of the above problem.

We assume that the disagreement point in a bargaining CO2 abatement game, in turn derived from the CO2 abatement game, is given by payoff function values at a Nash equilibrium in the CO2 abatement game[15]. In this bargaining CO2 abatement game, all players negotiate between each other concerning strategies taken for CO2 emission reduction rates from the year 2004 through to 2100. The disagreement point derived from a Nash equilibrium may then be implemented if some players disagree to a Nash bargaining solution. On the other hand, the Nash bargaining solution may be implemented if all players are in agreement.

3.3. The derivation method of two solutions

When using a dynamic EMEDA, there are four steps to finding a Nash equilibrium and a Nash bargaining solution. Firstly, obtaining payoffs of players $u = (u_r(\mu))_{r\in N}$ for each strategy profile $\mu = (\mu_r)_{r\in N}$ in S, we calculate the sum of discounted utilities using a dynamic EMEDA for each tuple of strategies. Next, we find a Nash equilibrium $\mu^* = (\mu^*_r)_{r\in N}$ through a payoff matrix, derived from the first step. Thirdly, we define a bargaining CO2 abatement game by setting a Nash equilibrium or $\tilde{\mu}$ to the disagreement point. That is,

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[14] See e.g., Thomson and Lensberg (1989) for details.

[15] We choose the less efficient Nash equilibrium since generally speaking multiple Nash equilibria may exist. When a Nash equilibrium does not exist, we assume the disagreement point to be where $\tilde{\mu} = (\tilde{\mu}_r)_{r\in N}$ such that $\tilde{\mu}_r = 0$ for all $r \in N$.

the disagreement point $d = (d_r)_{r \in N}$ is given by the payoff function values $u = (u_r)_{r \in N}$ at μ^*. Finally, we find a point which maximizes $\prod_{r \in N}(\bar{u}_r - d_r)$ with respect to $(\bar{u}_r)_{r \in N}$ in B and thus obtain a Nash bargaining solution $(\bar{b}_r)_{r \in N}$ and CO2 emissions reduction rates in a Nash bargaining solution $(\bar{\mu}_r)_{r \in N}$.

4. Game results

Simulated EMEDA results reflect both direct and indirect impacts. This is because CGE models incorporate interrelationships among regions, allowing us to also consider the indirect consequences when EMEDA focuses on global warming damages. As already mentioned, this research simulates a dynamic EMEDA to determine reduction rates of CO2 emissions for the three regions of Japan, China and the U.S. From hereon, we will discuss simulated dynamic EMEDA results by region for both reduction rates and economic impacts of climate change. Note that for this EMEDA simulation we use GAMS.

Solutions are calculated in two kinds of games: *a two-player game* in which $N = \{China, USA\}$ and *a three-player game* in which $N = \{Japan, China, USA\}$.

4.1. Two-player game with cooperative non-player behavior

First, we consider a case where the rate of time preference, ρ, is three percent. By calculation, we can find that both China and the U.S. always choose strategy 3 for payoff maximization[16]. This indicates that the unique Nash equilibrium $\mu^* = (7.5\%\mu'_{China}, 15\%\mu'_{USA})$ is obtained. With this Nash equilibrium, we consider a bargaining CO2 abatement game. A feasibility set F given by the dynamic EMEDA constitutes the set of points shown in Figure 5. In this figure, the horizontal axis represents payoffs for China, with the vertical axis being those for the U.S. By combining the two countries' choices of strategies, it is possible to illustrate the relationship between the two countries' behaviors. This figure shows change in payoffs by dashed curves when China changes its strategy in response to that of the U.S., while the solid curves represent payoff curves when the U.S. changes its strategy in accord with China's. By the curves we obtain an envelope like *utility possibility frontier*[17]. In this figure, the Nash bargaining solution is given by the point of contact between this envelope and the utility curve $U = (u_{China} - d_{China})(u_{USA} - d_{USA})$[18].

All results for solutions emerging from both the CO2 abatement and bargaining CO2 abatement games between China and the U.S. are compiled into Table 7, with solutions displayed as CO2 emission reduction rates. As can be seen from Table 7, we find in all cases that each player chooses a lower CO2 emissions reduction rate at the Nash equilibrium than at the Nash bargaining solution. Therefore it is clear that both China and the U.S. choose positive reduction rates of CO2 emissions in all scenarios where there is a rate of time preference. However, the level of reduction rates in the solutions is lower

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[16] The payoff matrices of China and the U.S. are given by Table 12 and 13, respectively. See Appendix A for details.

[17] See e.g., Mas-colell et al. (1995) for details.

[18] Rough and detailed utility curves are shown at the top and bottom of the figure, respectively.

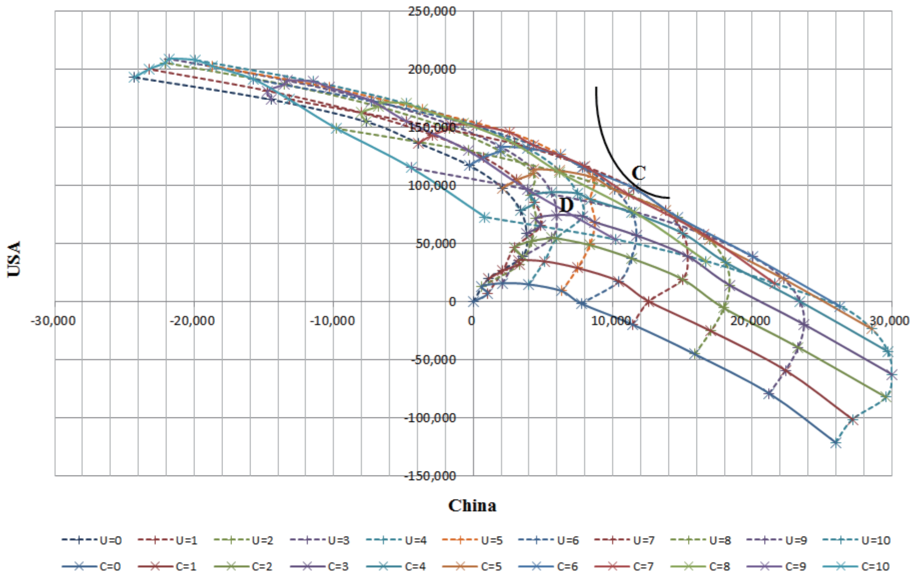

Figure 5: Two-Player Game with Nash Bargaining Solution at Point C and Nash Equilibrium at Point D

than that in the base scenario derived from the official announcements by each country. For instance, when the rate of time preference is 3%, as may be seen in Table 7, the CO2 reduction rate of China is 7.5% of the base scenario at the Nash equilibrium and 15% at the Nash bargaining solution. Regarding the U.S., the reduction rate of CO2 emissions is 15% of the base scenario at the Nash equilibrium and 35% at the Nash bargaining solution. These solutions suggest that it is difficult to attain CO2 abatements adequate for the goal of limiting post-industrial world temperature rises to within 2.0-2.4°C without suitable environmental policies in each region.

As the rate of time preference increases, the reduction rate remains either constant or decreasing in all solutions. This can be explained by the tendency of each player to consider current utility as more important than the utility of future periods, which diminishes as the rate of time preference increases.

Figure 6 provides a comparison of temperatures resulting from solutions emerging from other scenarios. The temperature rise at the year 2100 is approximately 3.21°C relative to the year 1900 at the Nash equilibrium and about 3.12°C in the Nash bargaining solution. Three important results may be drawn from Figure 6: 1) a 0.1°C temperature rise may be prevented through cooperation of countries; 2) the temperature falls by less than 0.9°C compared to the no-reduction scenario in the event of a payoff maximization for China and the U.S. even if the other regions choose CO2 reduction rates in the base scenario; and 3) even if cooperation is attained through a Nash bargaining solution, the excess rising temperature is about 0.8°C compared to the base scenario.

Rate of time preference	Nash equilibrium	Nash bargaining solution
1%	$(7.5\%\mu'_{China}, 20\%\mu'_{USA})$	$(20\%\mu'_{China}, 45\%\mu'_{USA})$
3%	$(7.5\%\mu'_{China}, 15\%\mu'_{USA})$	$(15\%\mu'_{China}, 35\%\mu'_{USA})$
5%	$(7.5\%\mu'_{China}, 15\%\mu'_{USA})$	$(12.5\%\mu'_{China}, 25\%\mu'_{USA})$
10%	$(5\%\mu'_{China}, 10\%\mu'_{USA})$	$(7.5\%\mu'_{China}, 15\%\mu'_{USA})$

Table 7: Nash Equilibrium and Nash Bargaining Solution in the Game of China and the U.S.: (China,USA)

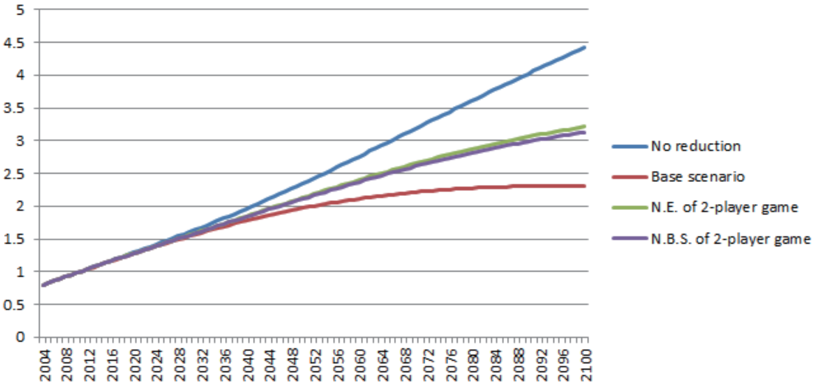

Figure 6: Comparison of Change in Temperature (°C above 1900) in the Two-Player Game

4.2. Two-player game with non-cooperative behavior from non-players

Next, we consider a case where each of the other regions refrains from reducing individual CO2 emissions. The results for solutions emerging out of both the CO2 abatement game and the bargaining CO2 abatement game between China and the U.S. are compiled into Table 8[19].

A comparison of Table 7 and 8 reveals that China chooses to increase its CO2 abatements for lower rates of time preference in both Nash equilibrium and Nash bargaining solution. This is because China, which has chosen lower CO2 reduction rates than the U.S., becomes willing to increase its CO2 emissions reduction levels to mitigate more aggressively the climate damage driven by mounting world CO2 emissions.

Figure 7 provides a comparison of temperature rises ensuing from solutions emerging from the scenarios where the other regions refrain from reducing CO2 emissions. The temperature rise at the year 2100 is approximately 4.35°C relative to the year 1900 at the Nash equilibrium and about 4.28°C at the Nash bargaining solution. With a discrepancy of less than 0.2°C between the no-reduction scenario and the Nash bargaining solution, it becomes apparent that even if both China and the U.S. were to voluntarily reduce CO2 emissions, a rapid rise of the average global temperature is unavoidable.

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[19] Payoff tables are 14 and Table 15 in Appendix A.

Rate of time preference	Nash equilibrium	Nash bargaining solution
1%	$(15\%\mu'_{China}, 20\%\mu'_{USA})$	$(25\%\mu'_{China}, 40\%\mu'_{USA})$
3%	$(12.5\%\mu'_{China}, 15\%\mu'_{USA})$	$(20\%\mu'_{China}, 35\%\mu'_{USA})$
5%	$(10\%\mu'_{China}, 15\%\mu'_{USA})$	$(12.5\%\mu'_{China}, 25\%\mu'_{USA})$
10%	$(2.5\%\mu'_{China}, 10\%\mu'_{USA})$	$(7.5\%\mu'_{China}, 20\%\mu'_{USA})$

Table 8: Nash Equilibrium and Nash Bargaining Solution in the Game of China and the U.S. when Other Regions not Reducing CO2 Emissions: (China,USA)

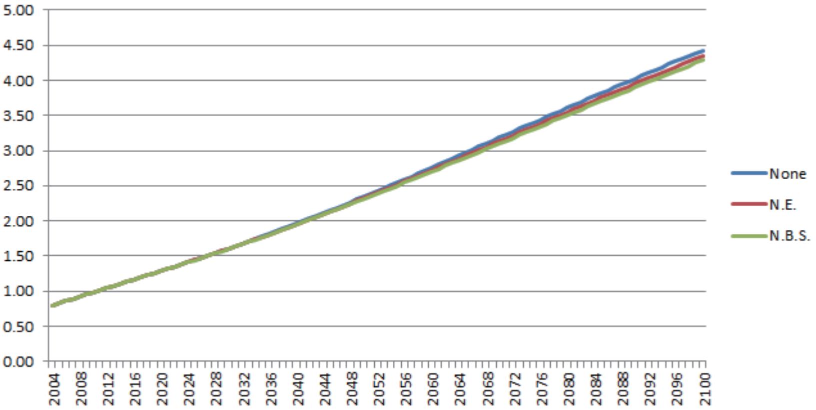

Figure 7: Comparison of Change in Temperature (°C above 1900) in the Two-Player Game when Other Regions not Reducing CO2 Emissions

4.3. The three-player game

Results of the CO2 abatement game and the bargaining CO2 abatement game among Japan, China and the U.S. are shown in Table 9[20]. In this table, in all cases each player chooses a lower reduction rate for CO2 emissions at the Nash equilibrium than at the Nash bargaining solution. It therefore becomes apparent that all three regions choose positive CO2 emission reduction rates in all cases of a rate of time preference. However, the level of the reduction rates in the solutions is lower than those in the base scenario as of the two-player game. For example, when the rate of time preference is 3%, the CO2 reduction rate for Japan is 5% at the Nash equilibrium and 25% at the Nash bargaining solution relative to the base scenario. Similarly, the CO2 reduction rate for China and the U.S. are respectively 10% and 20% at the Nash equilibrium and 15% and 30% at the Nash bargaining solution. Note that in the Nash bargaining solution Japan usually chooses strategy 5, which is the maximum reduction rate in Japan's strategy space, S_{Japan}. Compared with Japan's strategy at a Nash equilibrium, strategy 5 results in higher reduction rates at the Nash bargaining solution than at the Nash equilibrium. This indicates that the CO2 negotiations have large effects on rate at which Japan chooses to abate CO2 emissions.

Figure 8 shows temperature rises corresponding to solutions from the two-player and

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[20] The payoff matrices of the three players in the three-player game are shown in Appendix A.

Rate of time preference	Nash equilibrium	Nash bargaining solution
1%	$(5\%\mu'_{Japan}, 10\%\mu'_{China}, 20\%\mu'_{USA})$	$(25\%\mu'_{Japan}, 20\%\mu'_{China}, 40\%\mu'_{USA})$
3%	$(5\%\mu'_{Japan}, 10\%\mu'_{China}, 20\%\mu'_{USA})$	$(25\%\mu'_{Japan}, 15\%\mu'_{China}, 30\%\mu'_{USA})$
5%	$(5\%\mu'_{Japan}, 5\%\mu'_{China}, 10\%\mu'_{USA})$	$(25\%\mu'_{Japan}, 15\%\mu'_{China}, 30\%\mu'_{USA})$
10%	$(5\%\mu'_{Japan}, 5\%\mu'_{China}, 10\%\mu'_{USA})$	$(15\%\mu'_{Japan}, 10\%\mu'_{China}, 20\%\mu'_{USA})$

Table 9: Nash Equilibrium and Nash Bargaining Solution in the Game of Japan, China and the U.S.:(Japan,China,USA)

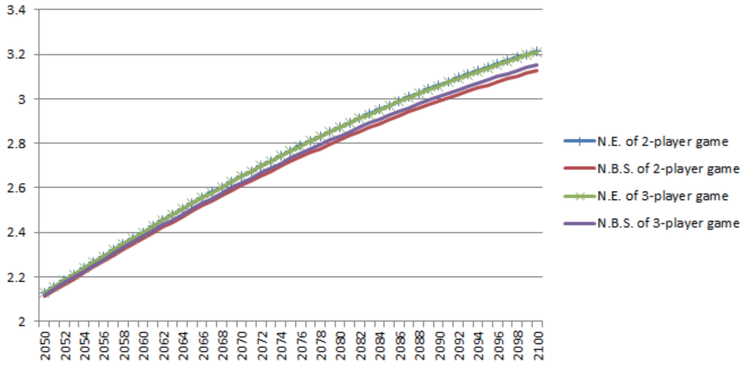

Figure 8: Comparison of Temperature Increase (°C Relative to 1900) in the Two-Player and Three-Player Games

three-player games. When comparing the results from both games, there is not a significant difference between the CO2 emissions reduction rates for China and the U.S. This is because the level of Japan's emissions is lower than the other players, especially in future periods.

5. Economic impacts of climate change

In this section, we define a benchmark scenario where each region suffers no climate damage. This scenario is then compared with the others, including those in the game solutions. To measure the overall economic impacts of climate change by region, we first focus on each region's rate of change in real GDP losses. Then, we calculate the rate of change in loss in real value-added by sector to determine discrepancies between regions and sectors. These loss ratios can be interpreted as the sum of the climate damage and the abatement costs.

			2-player game		3-player game	
Region	None	Base	N.E.	N.B.S.	N.E.	N.B.S.
Japan	-1.8 %	-2.6 %	-2.7 %	-2.7 %	-1.4 %	-1.4 %
China	-1.9 %	-7.5 %	-2.2 %	-2.2 %	-2.2 %	-2.2 %
USA	-1.2 %	-1.6 %	-0.9 %	-1.0 %	-0.9 %	-0.9 %
EU25_WEurope	-2.4 %	-2.3 %	-2.4 %	-2.4 %	-2.4 %	-2.5 %
FSU_EEurope	-0.7 %	-3.4 %	-3.7 %	-3.7 %	-3.7 %	-3.7 %
OAsiaOceania	-1.7 %	-12.3 %	-12.2 %	-12.2 %	-12.2 %	-12.2 %
OAmerica	-1.5 %	-3.8 %	-4.1 %	-4.1 %	-4.1 %	-4.1 %
Africa	2.5 %	-6.3 %	-6.4 %	-6.4 %	-6.4 %	-6.4 %

Table 10: Change in Real GDP (in US$ 2004 Equivalent) of All Regions in 2050

			2-player game		3-player game	
Region	None	Base	N.E.	N.B.S.	N.E.	N.B.S.
Japan	-9.3 %	-5.1 %	-6.9 %	-6.7 %	-5.2 %	-5.1 %
China	-2.9 %	-3.3 %	-2.4 %	-2.3 %	-2.4 %	-2.3 %
USA	-9.8 %	-4.7 %	-5.0 %	-4.9 %	-5.0 %	-4.9 %
EU25_WEurope	-13.4 %	-7.9 %	-10.3 %	-10.0 %	-10.3 %	-10.1 %
FSU_EEurope	-4.4 %	-6.5 %	-6.7 %	-6.7 %	-6.7 %	-6.7 %
OAsiaOceania	-7.3 %	-14.0 %	-14.5 %	-14.4 %	-14.5 %	-14.4 %
OAmerica	-8.7 %	-6.7 %	-8.2 %	-8.1 %	-8.2 %	-8.1 %
Africa	4.7 %	-1.6 %	-1.4 %	-1.4 %	-1.4 %	-1.4 %

Table 11: Change in Real GDP (in US$ 2004 Equivalent) of All Regions in 2100

5.1. Regional impacts

Table 10 displays rates of change in real GDP (in US$ 2004 equivalent) for all regions and the scenarios at the year 2050[21]. Focusing on real GDP in 2050, the best scenarios for each player are the no-reduction scenario (None) for China, the Nash equilibrium (N.E.) in the two-player game for the U.S., and finally, the Nash bargaining solution (N.B.S.) in the three-player game for Japan. Additionally, since higher reduction rates require more abatement costs, it can be seen that all players prefer the no-reduction scenario and game solutions to the base scenario (Base). This is especially so for China who bears more abatement costs (i.e., higher CO2 emissions reduction rates) than developed countries[22] such as Japan and the U.S. This discrepancy in abatement costs between developed countries and China can be explained by the result that the rate of economic growth in developed countries is lower than in the other countries. Note that when Japan participates in the three-player game, this leads to an increase in real GDP of Japan

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[21] The results of the two-player game in which the other regions do not reduce CO2 emissions are omitted in this section since the results are almost the same as those in the no-reduction scenario.

[22] For details, real GDP of the U.S., Japan, EU and other America increases as CO2 emissions are reduced.

because abatement costs drop as a result of cutting the rate at which CO2 emissions decline.

Table 11 represents rates of change in real GDP for all regions and scenarios at the year 2100. Here the Nash bargaining solution in the two-player game constitutes the best outcome for China, whereas it is the base scenario for Japan and the U.S. For the other regions, real GDP losses in the EU and other America increase by more than 1% as China and the U.S. deviate from the base scenario. On the other hand, FSU and other Asia and Oceania undergo an increase of less than 1%. For Africa, real GDP loss decreases.

Comparing Tables 10 and 11, we find that each region prefers higher CO2 reduction rates in the year 2100 than in 2050. This is due to worsening climate damage caused by continual temperature rise. Comparing the no-reduction scenario to other scenarios in the solutions for the three-player games, real GDP for Japan and the U.S. increases in both years as CO2 emissions are reduced, while Chinese real GDP decreases in 2050. This is for the reason that an increase in abatement costs for CO2 reduction exceeds the amount incurred from climate damage in China. In contrast, in developed countries abatement costs are justified. This is for the reason that increased climate damages are superior to the costs required to pursue higher CO2 emission reduction rates.

These results suggest that a reduction in CO2 emissions is more beneficial to developed nations than for other countries. This implies that international cooperation for climate change mitigation requires higher abatement costs in developed countries in order to ensure fairness between developed and developing countries.

Next, we measure effects of CO2 reduction on the world economy from 2004 to 2100 in a situation where certain regions behave either cooperatively or in self-interest. Several scenarios are developed in the games including the Nash equilibrium and the Nash bargaining solution. Figure 9 compares net present value (NPV) of real GDP loss for these scenarios with respect to the benchmark where each region suffers no climate damage and the discount rate of real GDP loss is 3 percent per annum. Comparing the game solutions to no-reduction scenarios, we find that real GDP losses of Japan and the U.S. are improved by participation in the CO2 abatement games, though China experiences a deterioration in real GDP. Considered at a global level, the base scenario emerges as the least attractive since total abatement costs are higher than in the other scenarios.

Figure 10 shows the ratio of NPV of real GDP loss in each region with respect to the benchmark scenario. For China, FSU, other Asia and Oceania, other American countries and Africa, CO2 reductions lead to a deterioration in real GDP loss ratio. Especially other Asia and Oceania and Africa increase their real GDP loss ratio rapidly. On the other hand, for Japan, the U.S. and EU, each real GDP loss ratio is improved through CO2 reductions. Moreover, comparing the scenarios in the solutions for the three-player games to the base scenario, we find that all players improve real GDP loss ratio by participation in the CO2 abatement games. This is especially so for China, who can reduce its damage by more than 3% NPV of its real GDP.

Finally, Table 11 shows annual change in real GDP loss ratios for each player, in several scenarios. Comparing the base scenario with that in the Nash bargaining solution

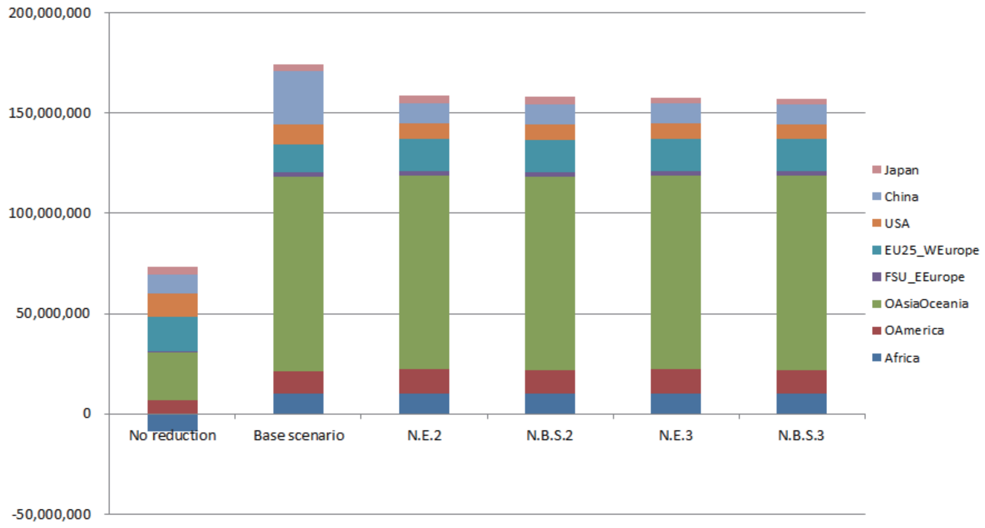

Figure 9: NPV of Real GDP Loss of Each Region by Scenario (in Millions of US$ 2004 Equivalent)

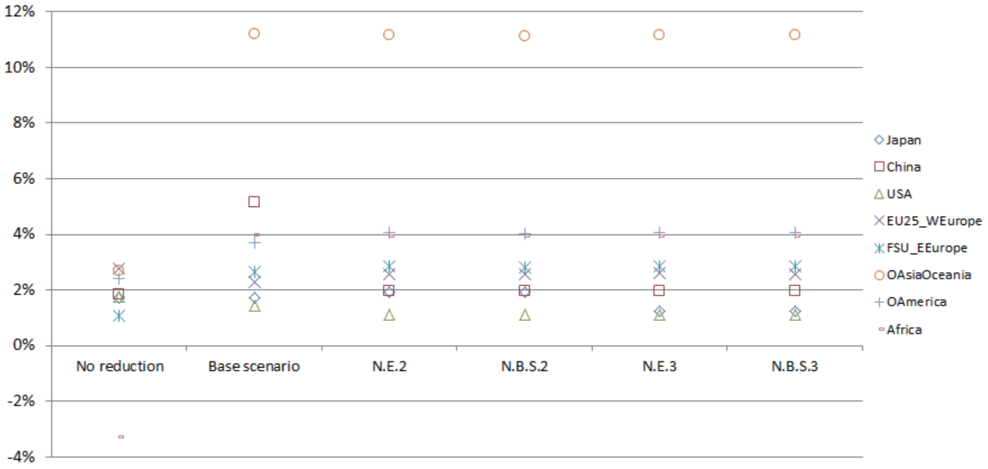

Figure 10: The Ratio of NPV of Real GDP Loss of Each Region by Scenario

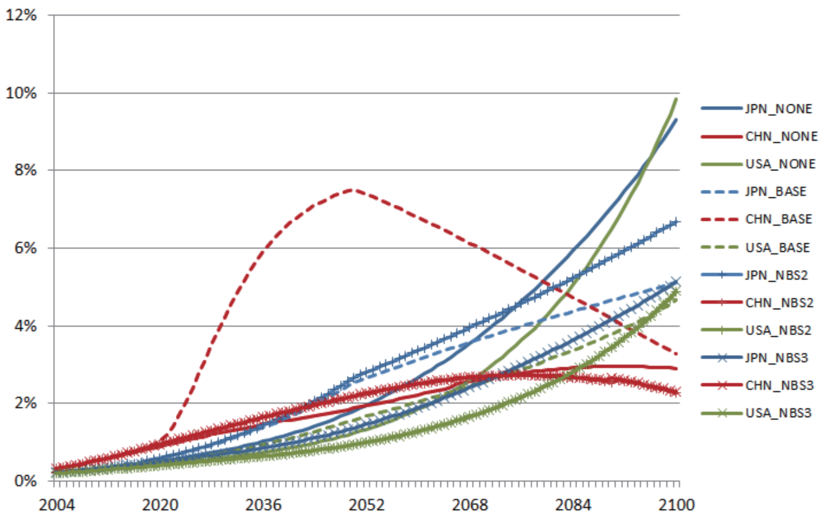

Figure 11: Comparison of GDP of Three Players in Several Scenarios

for the two-player game (NBS2), both China and the U.S. emerge as better off in most years. This is due to a reduction in abatement costs, as lesser CO2 reduction rates are pursued in NBS2. It should be noted that Japan comes out worse off because world CO2 emissions increase as a result of strategic behaviors from China and the U.S. Furthermore, Japan finds itself in an advantageous situation as a result of choosing lower CO2 reduction rates in NBS3 through comparing NBS3 with NBS2. Note that real GDP for the other two players rarely changes. The lesson here is that a region's participation in the game can prove beneficial for itself, but not so for the others.

5.2. Sectoral impacts

Previous literature has emphasized that damages or benefits from climate change differ not only by region, but also by sector (e.g., Eboli et al., 2010; Tol, 2002; Washida et al., 2013a). In this subsection we determine in more detail the extent to which losses in real value-added for each sector may be improved or worsened in each region when reducing CO2 emissions. To obtain rates of change for real value-added loss by sector in the dynamic EMEDA, a range of scenarios are compared to the benchmark.

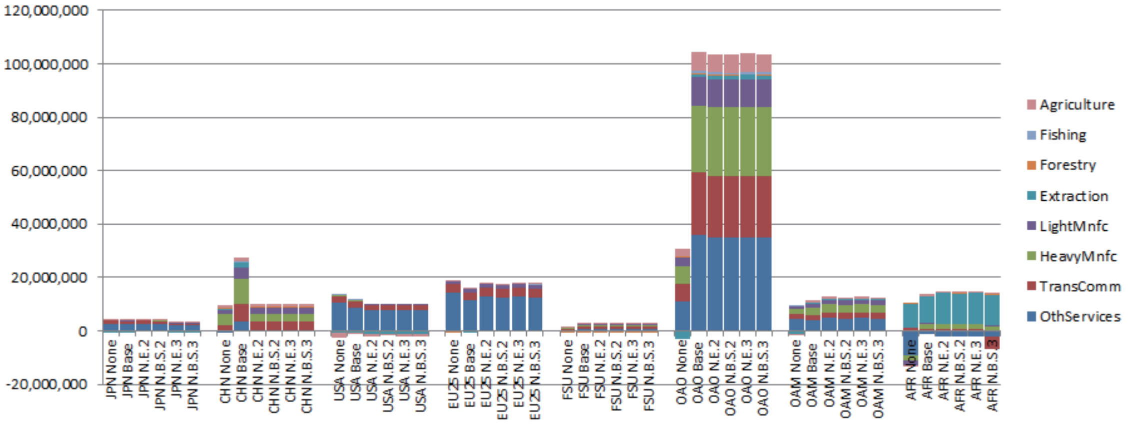

Figure 12: NPV of Real Value-Added Loss of Each Country by Sector (in Millions of US$ 2004 Equivalent)

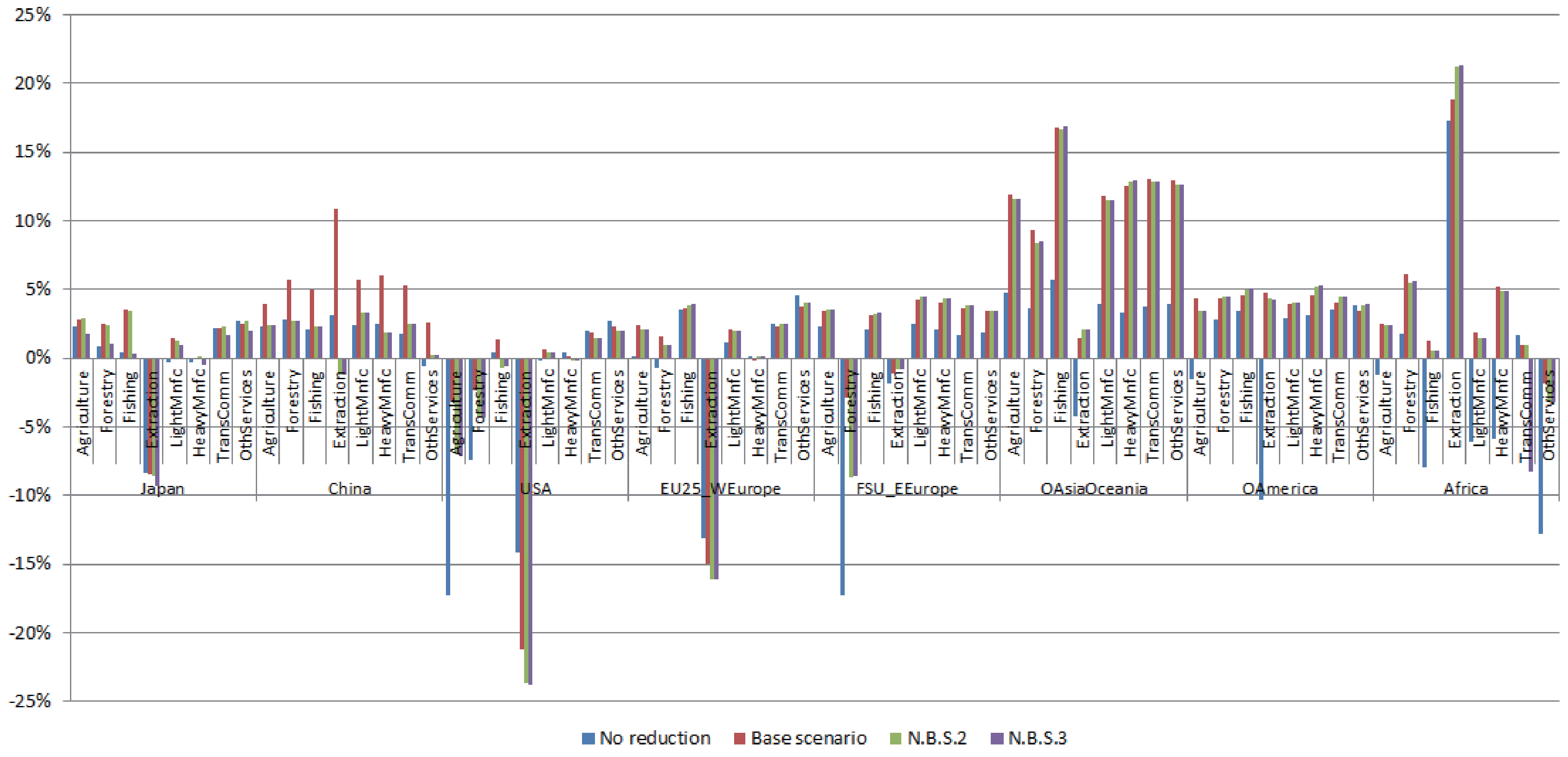

Figure 13: Rate of Change in Real Value-added Loss of the World in Several Scenarios

First, we measure amounts of the NPV of losses in real value-added for all regions. Figure 12 presents the NPV of real value-added losses experienced in each region by sector from 2004 to 2100. As can be seen, losses in real value-added for several sectors in Japan, China, the U.S., EU and other America are improved by pursuing CO2 reductions, in comparison to the base scenario. However, all sectors in the other three regions worsen.

In Figure 12, it can be confirmed that in some regions such as Japan, the U.S. and EU, sectoral damage in the services category such as transport and communication (TransComm) and other services (OthServices) accounts for the majority of losses. On the other hand, sectoral damage in manufacturing categories such as light manufacturing (LightMnfc) and heavy manufacturing (HeavyMnfc) and the services category are most significant in other regions such as China, FSU, other Asia and Oceania, and other American countries. For Africa, the extraction sector experiences the most severe losses.

Next, we calculate rates of change in the NPV of real value-added loss for all regions. Results for the period 2004-2100 for all scenarios including the no-reduction scenario, the base scenario, Nash bargaining solution for the two-player game, and that of the three-player game are displayed in Figure 13[23]. The following results are obtained from this figure. Firstly, in all regions and for the majority of sectors except extraction and heavy manufacturing, the real-value added for the no-reduction scenario is higher than that for the base scenario. This shows that excessive CO2 emissions abatement leads to a deterioration of overall economy. Secondly, when Japan, China and the U.S. participate in the CO2 abatement games, a reduction in CO2 emissions boosts real value-added in several regions. Positive sectoral impacts can be found in several sectors such as heavy manufacturing in Japan, agriculture in the U.S., extraction in China and EU, forestry in FSU, and other services in Africa. Thirdly, in light manufacturing, real value-added consistently decreases in response to reductions in CO2 emissions. Therefore, it could be argued that additional policies may be required in order to improve the economies of all sectors. Fourthly, for agriculture, real value-added for both the U.S. and EU rapidly decreases as CO2 is reduced, while both Japan and China see an increase since the diminution of their imports of agricultural goods exceeds that of their exports. Fifthly, for the services category real value-added for developed countries such as Japan, U.S. and EU see an increase as the domestic demand for services expands as a result of CO2 reductions. Finally, real value-added for the extraction sector diminishes in most regions except Africa. This probably reflects the large share represented by the extraction sector in the overall African economy, which will be accelerated by rapid economic growth on SSP1. These results suggest that global warming mitigation may dramatically alter the global economic structure.

Finally, we consider the annual change in real value-added loss ratios for each player by industry. Figure 14, 15 and 16 show the transition of real value-added loss ratio for China, the U.S. and Japan, respectively. The three industries in these figures are defined as follows: primary industry (PI) consisting of Agriculture, Forestry and Fishing;

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[23] The results in the Nash equilibrium are omitted since the results are almost the same as those of Nash bargaining solution.

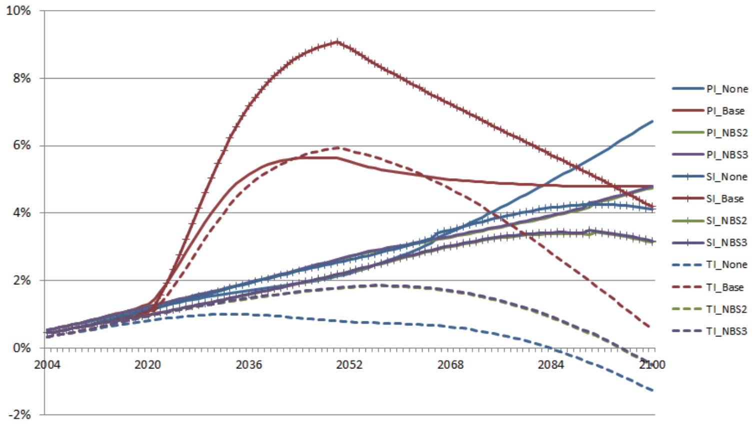

Figure 14: Rate of Change in Real Value-added loss of Three Industries of China in Several Scenarios

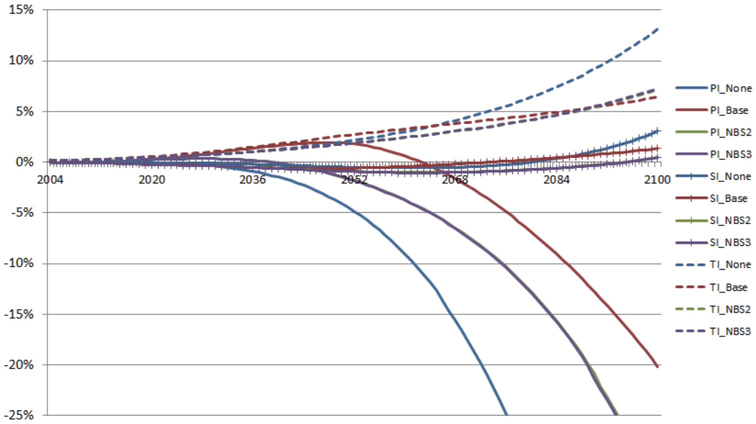

Figure 15: Rate of Change in Real Value-added loss of Three Industries of the U.S. in Several Scenarios

secondary industry (SI) composed of Extraction, LightMnfc and HeavyMnfc; and tertiary industry (TI) as the sum of TransComm and OthServices.

In Figures 14, 15 and 16 we find the following results. Firstly, there is always a player who experiences a decrease in real value-added loss for each industry. As shown in Figures 6 and 8, damages from climate change and global warming become more severe as time passes and the temperature rises. This means that climate damages of each player can be mitigated by trade among regions. Secondly, for the heavy manufacturing in particular in the secondary industry, the real value-added losses of China and the U.S. are improved in the scenarios derived from the Nash bargaining solutions compared to the others. Finally, Japan's real value-added loss is also improved in the primary and tertiary industries. These results suggest the varying degree of importance placed on the profit maximization for different industries in each region.

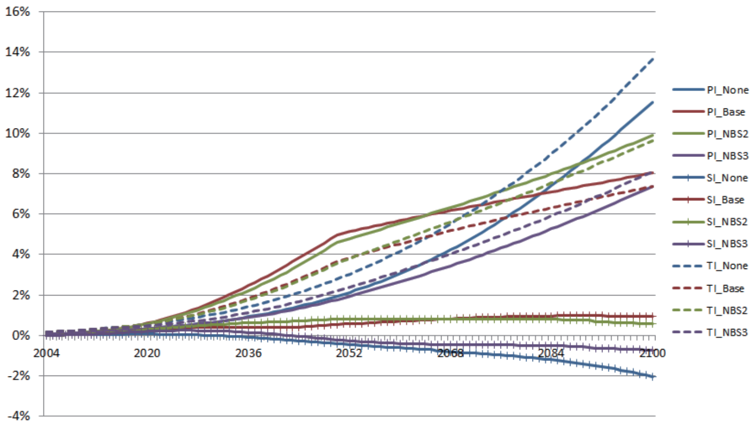

Figure 16: Rate of Change in Real Value-added loss of Three Industries of Japan in Several Scenarios

6. Concluding Remarks

In summing up the main lessons from this study, simulated results from the dynamic EMEDA using the CGE approach and game theory indicate that: 1) each player chooses a positive lower reduction rate of CO2 emissions at the Nash equilibrium than at the Nash bargaining solution; 2) simulated CO2 emissions under the reduction rates emerging as solutions from both games are higher than official reduction pledges made by Japan, China and the U.S.; 3) an increase in the rate of time preference causes a decrease in the reduction rates of CO2 emissions; 4) total climate impacts in developed countries are less than those of the developing countries, some of which lose more than 10% of their real GDPs in each scenario; 5) an extra 0.8°C temperature rise occurs by the year 2100 with the U.S. and China's deviation from the scenario proposed by international society. This leads to increased climate damages in other regions, most particularly in other developed countries, who experience a loss of up to 1% in real GDP; 6) for the secondary industry sector, real value-added losses of both China and the U.S. are improved in the scenarios derived from game solutions, even if real GDP loss of China is worsened; and 7) positive sectoral impacts may be observed in several regions such as Japan, China, the U.S., EU, FSU and Africa.

These results suggest that it will be difficult to attain CO2 abatements adequate for the goal of limiting post-industrial world temperature rises to within 2.0-2.4°C without suitable environmental policies. It should therefore be noted that when considering abatement costs, a reduction in CO2 emissions is not necessarily beneficial to all countries involved. Especially in the case of developing countries, real GDP tends to decrease as CO2 emissions are reduced. This is principally because abatement costs are higher in these countries in all scenarios, and the economies in developing countries are forecasted to grow rapidly throughout this century. Moreover, deviation from international agreements on CO2 reduction causes additional damage to each region. It is therefore essential that this unfairness should be corrected in order to secure the participation and cooperation of developing countries in the goal of reducing global CO2 emissions.

In this study, we have assumed that each region maximizes its payoff, which is given by the sum of discounted utilities. In reality, however, the interests of several parties will affect the outcome of agreements regarding CO2 emission reductions. Our results imply that there is a possibility that some sectors in each region may suffer much economic damage as a result of climate agreements; a scenario which is characterized by the Nash bargaining solution. Thus this prospect of incurring economic losses constitutes a potential hampering to climate agreements as parties in the sector in question seek to preserve their own interests. This situation therefore illustrates the difficulty in reaching an agreement for CO2 reductions.

Appendix A. Payoff Matrices

Appendix A shows payoff matrices calculated by the dynamic EMEDA. In each table, payoffs are normalized to zero when each player chooses strategy 0, that is, no reduction of CO2 emissions.

						USA					
		0	1	2	3	4	5	6	7	8	9	10
China	0	0	1,030	600	2,080	3,960	6,340	7,740	11,410	15,870	21,200	25,960
	1	1,100	2,130	3,330	3,220	5,100	7,480	10,450	12,590	17,040	22,380	27,180
	2	3,520	2,960	4,150	5,630	5,970	8,350	11,320	14,990	17,960	23,290	29,580
	3	3,810	4,840	4,490	5,960	7,840	8,720	11,690	15,360	18,370	23,710	30,000
	4	3,400	4,420	4,120	5,600	7,470	8,390	11,370	15,040	18,090	23,430	29,720
	5	2,090	3,120	4,300	4,330	6,200	8,570	10,150	13,820	16,920	22,250	28,550
	6	-290	730	1,920	1,990	3,860	6,230	7,850	11,520	14,670	20,010	26,300
	7	-3,940	-2,920	-1,730	-1,610	250	2,620	4,290	7,960	11,160	16,500	21,590
	8	-7,680	-8,010	-6,830	-6,660	-4,790	-3,670	-700	2,960	6,220	11,550	16,700
	9	-14,450	-14,730	-13,540	-13,330	-11,460	-10,290	-7,320	-4,810	-350	3,870	10,180
	10	-24,270	-23,250	-22,070	-21,810	-19,940	-18,720	-15,750	-13,190	-9,790	-4,450	840

Table 12: Payoff Matrix for China ($\rho = 3\%$) in the Two-Player Game

						USA					
		0	1	2	3	4	5	6	7	8	9	10
China	0	0	7,000	13,180	15,920	14,900	9,140	-1,580	-19,590	-45,030	-78,760	-120,910
	1	19,810	26,820	32,280	35,740	34,720	28,960	17,520	220	-25,230	-58,970	-101,130
	2	38,880	46,600	52,060	54,810	54,500	48,740	37,300	19,290	-5,460	-39,210	-82,070
	3	58,600	65,610	71,780	74,530	73,520	68,450	57,020	39,000	14,240	-19,510	-62,380
	4	78,230	85,240	91,410	94,160	93,150	88,080	76,640	58,630	33,850	90	-42,790
	5	97,750	104,760	110,240	113,680	112,670	106,910	96,150	78,130	53,340	19,580	-23,310
	6	117,130	124,150	129,620	133,060	132,050	126,290	115,520	97,500	72,700	38,930	-3,970
	7	136,360	143,380	148,860	152,290	151,280	145,520	134,740	116,710	91,890	58,120	15,860
	8	154,740	162,430	167,910	171,340	170,320	165,220	153,770	135,740	110,910	77,130	34,840
	9	173,610	181,290	186,770	190,190	189,170	184,060	172,610	155,210	129,720	96,560	53,630
	10	192,920	199,940	205,420	208,820	207,810	202,680	191,230	173,820	148,930	115,140	72,800

Table 13: Payoff Matrix for the U.S. ($\rho = 3\%$) in the Two-Player Game

		USA										
		0	1	2	3	4	5	6	7	8	9	10
China	0	0	1,240	2,620	4,280	6,320	8,830	9,480	13,230	17,720	23,060	29,310
	1	3,240	4,470	5,850	5,070	7,100	9,620	12,700	16,450	20,950	26,280	32,530
	2	3,700	4,920	6,310	7,960	10,000	12,510	15,590	19,340	23,830	29,170	35,420
	3	6,020	7,240	8,620	10,270	12,310	14,810	17,900	21,640	26,140	31,470	37,720
	4	7,530	8,750	10,130	11,780	13,810	16,320	19,400	23,140	27,640	32,970	39,220
	5	8,030	9,250	10,620	12,270	14,300	16,800	19,880	23,630	25,700	31,030	37,290
	6	7,310	8,530	9,900	11,540	13,570	16,070	16,730	20,470	24,970	30,300	36,560
	7	5,180	6,390	7,760	6,990	9,010	11,520	14,590	18,340	22,830	28,170	34,420
	8	-980	230	1,600	3,250	5,270	7,770	10,850	14,590	19,090	24,430	30,680
	9	-6,520	-5,310	-3,940	-2,300	-270	2,230	5,310	9,050	13,550	18,880	25,140
	10	-14,070	-12,850	-11,490	-9,840	-7,820	-5,320	-2,240	1,500	6,000	11,340	15,210

Table 14: Payoff Matrix for China when Other Regions not Reducing CO2 Emissions

		USA										
		0	1	2	3	4	5	6	7	8	9	10
China	0	0	6,910	12,300	15,000	13,980	8,260	-2,310	-20,160	-45,370	-78,790	-121,250
	1	18,850	25,770	31,170	34,640	33,630	27,910	16,570	-1,270	-26,490	-59,920	-102,370
	2	38,470	45,390	50,790	53,510	52,490	46,780	35,440	17,600	-7,620	-41,050	-83,510
	3	57,280	64,210	69,620	72,340	71,330	65,620	54,280	36,440	11,220	-22,210	-64,680
	4	76,030	82,970	88,390	91,110	90,110	84,400	73,070	55,230	30,010	-3,430	-45,910
	5	94,720	101,660	107,090	109,820	108,810	103,110	91,780	73,940	49,490	16,050	-26,440
	6	113,310	120,270	125,690	128,430	127,430	121,730	111,180	93,330	68,110	34,660	-7,820
	7	131,810	138,770	144,200	147,710	146,720	141,020	129,690	111,850	86,620	53,180	10,680
	8	150,950	157,910	163,350	166,100	165,110	159,420	148,090	130,250	105,020	71,570	29,070
	9	169,180	176,160	181,600	184,350	183,370	177,680	166,360	148,510	123,280	89,820	47,320
	10	187,280	194,260	199,710	202,460	201,480	195,790	184,470	166,630	141,400	107,940	66,190

Table 15: Payoff Matrix for the U.S. when Other Regions not Reducing CO2 Emissions

		USA					
	JPN=0	0	1	2	3	4	5
China	0	0	3,447	6,883	10,653	14,585	19,003
	1	8,792	12,111	15,671	19,316	23,369	27,667
	2	17,316	20,756	24,195	27,957	31,892	36,304
	3	25,712	29,034	32,585	36,342	40,279	44,685
	4	33,652	37,083	40,629	44,380	48,318	52,718
	5	41,277	44,702	48,242	51,986	56,017	60,409

		USA					
	JPN=1	0	1	2	3	4	5
China	0	217	3,665	7,101	10,871	14,803	19,221
	1	9,010	12,329	15,889	19,535	23,587	27,885
	2	17,534	20,974	24,413	28,175	32,111	36,522
	3	25,930	29,252	32,804	36,560	40,497	44,903
	4	33,870	37,301	40,847	44,598	48,634	52,937
	5	41,495	44,920	48,460	52,204	56,235	60,627

		USA					
	JPN=2	0	1	2	3	4	5
China	0	25	3,473	6,909	10,678	14,611	19,029
	1	8,817	12,137	15,697	19,342	23,395	27,693
	2	17,342	20,781	24,220	27,983	32,030	36,330
	3	25,737	29,059	32,611	36,368	40,305	44,711
	4	33,678	37,109	40,655	44,405	48,442	52,744
	5	41,303	44,728	48,268	52,012	56,042	60,434

		USA					
	JPN=3	0	1	2	3	4	5
China	0	-890	2,558	5,994	9,763	13,696	18,114
	1	7,902	11,222	14,782	18,427	22,480	26,893
	2	16,427	19,866	23,305	27,067	31,115	35,415
	3	24,822	28,144	31,696	35,453	39,390	43,796
	4	32,762	36,194	39,739	43,490	47,526	51,924
	5	40,387	43,812	47,352	51,096	55,127	59,519

		USA					
	JPN=4	0	1	2	3	4	5
China	0	-2,806	642	4,077	7,847	11,779	16,197
	1	5,986	9,305	12,865	16,511	20,563	24,977
	2	14,510	17,950	21,389	25,151	29,198	33,498
	3	22,905	26,227	29,779	33,535	37,577	41,878
	4	30,954	34,276	37,822	41,573	45,609	50,006
	5	38,470	41,895	45,434	49,179	53,209	57,601

		USA					
	JPN=5	0	1	2	3	4	5
China	0	-5,983	-2,536	900	4,669	8,601	13,019
	1	2,808	6,128	9,687	13,332	17,385	21,798
	2	11,332	14,771	18,210	21,972	26,019	30,319
	3	19,727	23,049	26,600	30,356	34,398	38,699
	4	27,775	31,097	34,643	38,393	42,429	46,826
	5	35,392	38,715	42,255	45,999	50,029	54,420

Table 16: Payoff Matrix for Japan ($\rho = 3\%$) in the Three-Player Game

		USA					
JPN=0		0	1	2	3	4	5
China	0	0	550	3,920	7,640	15,770	25,810
	1	1,830	4,060	5,830	11,180	17,760	29,380
	2	3,250	3,920	7,270	11,120	19,240	29,420
	3	-540	1,660	3,560	7,500	15,620	25,890
	4	-8,000	-7,190	-5,210	-1,170	6,950	17,330
	5	-23,460	-22,560	-20,470	-16,340	-9,370	1,160

		USA					
JPN=1		0	1	2	3	4	5
China	0	180	730	4,090	7,820	15,940	25,980
	1	2,010	4,230	6,000	11,350	17,930	29,550
	2	3,430	4,100	7,440	11,290	19,410	29,590
	3	-370	1,830	3,730	7,670	15,790	26,060
	4	-7,830	-7,020	-5,030	-1,000	5,870	17,500
	5	-23,290	-22,390	-20,300	-16,170	-9,200	1,330

		USA					
JPN=2		0	1	2	3	4	5
China	0	400	950	4,320	8,040	16,170	26,200
	1	2,230	4,460	6,220	11,570	18,150	29,770
	2	3,650	4,320	7,660	11,510	18,190	29,810
	3	-150	2,050	3,950	7,890	16,010	26,280
	4	-7,610	-6,800	-4,810	-780	6,090	17,720
	5	-23,070	-22,170	-20,080	-15,950	-8,980	1,550

		USA					
JPN=3		0	1	2	3	4	5
China	0	710	1,260	4,620	8,350	16,470	26,510
	1	2,540	4,760	6,530	11,880	18,460	28,590
	2	3,950	4,630	7,970	11,820	18,490	30,120
	3	160	2,360	4,250	8,190	16,310	26,590
	4	-7,300	-6,500	-4,510	-470	6,390	16,820
	5	-22,760	-21,860	-19,780	-15,640	-8,680	1,850

		USA					
JPN=4		0	1	2	3	4	5
China	0	1,130	1,690	5,050	8,770	16,900	26,930
	1	2,960	5,190	6,950	12,300	18,880	29,010
	2	4,380	5,050	8,390	12,240	18,920	30,540
	3	580	2,780	4,680	8,620	15,380	27,010
	4	-8,270	-6,070	-4,090	-50	6,810	17,240
	5	-22,340	-21,440	-19,360	-15,220	-8,250	2,280

		USA					
JPN=5		0	1	2	3	4	5
China	0	1,710	2,260	5,620	9,340	17,470	27,510
	1	3,540	5,760	7,520	12,870	19,450	29,580
	2	4,950	5,620	8,960	12,810	19,490	31,110
	3	1,150	3,350	5,250	9,190	15,950	27,580
	4	-7,700	-5,500	-3,520	520	7,380	17,810
	5	-23,070	-20,870	-18,790	-14,650	-7,680	2,850

Table 17: Payoff Matrix for China ($\rho = 3\%$) in the Three-Player Game

				USA			
JPN=0		0	1	2	3	4	5
China	0	0	13,180	14,900	-1,580	-45,030	-120,890
	1	39,570	52,040	54,480	37,280	-5,470	-82,070
	2	78,190	91,370	93,110	76,610	33,140	-42,790
	3	117,090	129,570	132,010	115,490	72,000	-3,970
	4	154,680	167,860	170,280	153,740	110,240	34,210
	5	192,200	205,370	207,770	191,200	148,320	72,230

				USA			
JPN=1		0	1	2	3	4	5
China	0	1,310	14,480	16,200	-280	-43,720	-119,580
	1	40,880	53,350	55,790	38,590	-4,170	-80,760
	2	79,500	92,680	94,420	77,920	34,450	-41,480
	3	118,400	130,880	133,320	116,800	73,310	-2,660
	4	155,990	169,170	171,590	155,050	112,200	35,520
	5	193,520	206,680	209,080	192,510	149,630	73,540

				USA			
JPN=2		0	1	2	3	4	5
China	0	2,630	15,800	17,520	1,040	-42,400	-118,270
	1	42,200	54,660	57,100	39,910	-2,850	-79,440
	2	80,820	94,000	95,740	79,240	36,460	-40,160
	3	119,720	132,210	134,640	118,120	74,630	-1,350
	4	157,310	170,490	172,910	156,370	113,520	36,840
	5	194,840	208,000	210,400	193,840	150,950	74,860

				USA			
JPN=3		0	1	2	3	4	5
China	0	3,970	17,140	18,860	2,380	-41,070	-116,930
	1	43,540	56,000	58,440	41,250	-1,510	-77,410
	2	82,160	95,340	97,080	80,580	37,800	-38,830
	3	121,060	133,550	135,980	119,460	75,970	-10
	4	158,650	171,830	174,250	157,710	114,860	38,820
	5	196,180	209,340	211,750	195,180	152,290	76,200

				USA			
JPN=4		0	1	2	3	4	5
China	0	5,330	18,500	20,230	3,740	-39,700	-115,570
	1	44,900	57,370	59,810	42,610	-140	-76,040
	2	83,530	96,710	98,450	81,940	39,160	-37,460
	3	122,430	134,910	137,340	120,820	78,010	1,360
	4	160,710	173,200	175,620	159,080	116,230	40,190
	5	197,550	210,710	213,110	196,540	153,660	77,560

				USA			
JPN=5		0	1	2	3	4	5
China	0	6,730	19,900	21,620	5,140	-38,300	-114,170
	1	46,300	58,770	61,210	44,010	1,260	-74,650
	2	84,930	98,110	99,850	83,340	40,560	-36,060
	3	123,830	136,310	138,750	122,230	79,410	2,760
	4	162,110	174,600	177,020	160,480	117,630	41,590
	5	199,610	212,110	214,520	197,950	155,060	78,960

Table 18: Payoff Matrix for the U.S. ($\rho = 3\%$) in the Three-Player Game

Appendix B. Results of a two-player game including the base scenario

Strategy	China	USA
0	0	0
1	$25\%\mu'_{China}$	$25\%\mu'_{USA}$
2	$50\%\mu'_{China}$	$50\%\mu'_{USA}$
3	$75\%\mu'_{China}$	$75\%\mu'_{USA}$
4	μ'_{China}	μ'_{USA}

Table 19: Strategies of China and USA in the Two-Player Game Including the Base Scenario

		USA				
		0	1	2	3	4
China	0	0	-24,270	-256,060	-996,710	-2,955,340
	1	6,340	-18,720	-248,010	-988,230	-2,946,010
	2	25,960	840	-225,100	-964,850	-2,921,790
	3	73,370	47,120	-175,810	-915,080	-2,871,160
	4	156,090	133,010	-89,580	-828,330	-2,783,550

Table 20: Payoff Matrix for China ($\rho = 3\%$) in the Two-Player Game Including the Base Scenario

		USA				
		0	1	2	3	4
China	0	0	192,920	363,940	506,380	654,800
	1	9,140	202,680	372,390	514,700	662,740
	2	-120,910	72,800	240,380	382,270	529,620
	3	-499,470	-305,530	-140,420	560	146,670
	4	-1,224,890	-1,033,820	-870,150	-730,770	-586,650

Table 21: Payoff Matrix for the U.S. ($\rho = 3\%$) in the Two-Player Game Including the Base Scenario

Discount rate	Nash equilibrium	Nash bargaining solution
1%	$(0, 25\%\mu'_{USA})$	$(25\%\mu'_{China}, 50\%\mu'_{USA})$
3%	$(0, 25\%\mu'_{USA})$	$(0, 25\%\mu'_{USA})$
5%	(0, 0)	(0, 0)
10%	(0, 0)	(0, 0)

Table 22: Nash Equilibrium and Nash Bargaining Solution in the Game Including the Base Scenario

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