Title	Game-theoretic models of human behavior : Malaria prevention and emissions trading
Author(s)	本城, 慶多
Citation	北海道大学. 博士(環境科学) 甲第11784号
Issue Date	2015-03-25
DOI	10.14943/doctoral.k11784
Doc URL	http://hdl.handle.net/2115/59327
Type	theses (doctoral)
File Information	Keita_Honjo.pdf

博士論文

Game-theoretic Models of Human Behavior: Malaria Prevention and Emissions Trading

（人間行動のゲーム理論モデル〜マラリア予防と排出権取引を例として）

北海道大学大学院環境科学院

本城 慶多

Keita Honjo

Acknowledgments

First of all, I am grateful to Akiko Satake for her educational support. She helped me start my career as an environmental researcher. I would like to thank Takashi Koyama, Takenori Takada, Keiichiro Tokita, and Yasuhiro Yamanaka for fruitful comments on this doctoral thesis. Thanks to Luis Fernando Chaves, Akira Kaneko, and Noboru Minakawa, I could tackle an interesting problem in malaria epidemiology. Masahiko Fujii helped me find a position. I received financial support from Japan Society for the Promotion of Science between April 2012 and March 2015. Finally, I thank my parents for their support in daily life.

Contents

Chapter 1

Introduction

How should we act in the society? Economists have approached this question using the assumption of economic human (*homo economicus*). An economic human is an individual with complete rationality. The economic human calculates all costs and benefits associated with its action, and chooses the optimal action to maximize the net benefit. The basic competitive model in economics describes a market in which many rational individuals act according to price information [1]. In a competitive market, all costs and benefits associated with goods are included in price. Moreover, no one has market power to control price. Therefore each agent needs not to consider other agents' actions, and can choose the optimal action based on price information, the budget constraint, and the utility function. Kenneth Arrow and Gerard Debreu demonstrated that a competitive market achieves a Pareto efficient allocation of resources [2, 3]. This result, which is well known as the first fundamental theorem of welfare economics, shows an ideal society formed by economic humans.

Clearly, the society described by the basic competitive model is different from the real society. Competition in our society is usually imperfect, and the assumption of the basic competitive model is not realistic. Under imperfect competition, we are forced to play *games*. A game is a situation in which each agent's benefit is influenced by other agents' actions. Our society consists of various kinds of games: job hunting, investing, marrying, bargaining, and wars. Game theory, established by John von Neumann and Oskar Morgenstern [4], is a useful tool to analyze decision making under games. Game theory has been developed mainly in economics, but now has a variety of applications (e.g. evolutionary game theory in biology [5]).

Games are classified into two major groups: non-cooperative and cooperative. Non-cooperative games focus on decision making of self-interest individuals. Participants in a game are called players. Each player chooses a strategy from a set of strategies. A player's payoff is determined by a combination of strategies for all players (a strategy profile). A strategy profile achieved by players is a solution of a non-cooperative game. The Nash equilibrium, which was formulated by John Nash [6, 7], is the most popular solution concept in non-cooperative games. The Nash equilibrium gives the set of profiles at which every player's strategy is the best response to other players' strategies. Under the Nash equilibrium, no one has incentive to change its strategy. The Nash equilibrium is used to describe decision making of rational individuals. It is important that the Nash equilibrium may not satisfy Pareto efficiency. A well-known example is the prisoner's dilemma [1, 5]. In the prisoner's dilemma, the players are attracted to a Pareto inefficient Nash equilibrium. The prisoner's dilemma clearly shows that the society formed by economic humans is not always efficient. The mismatch between individual and social rationality is called a social dilemma [8]. Social dilemmas are closely relevant to environmental problems [9, 10].

We often cooperate with other people to gain larger benefits (e.g. coalitions, cartels, and international agreements). Benefits from cooperation are allocated to the members through bargaining. Cooperative games (coalitional games) focus on a set of win-win payoff allocations which satisfy both individual and social rationality. The basis of coalitional games was given by von Neumann and Morgenstern [4]. In a coalitional game, each player is allowed to form a coalition with other players. Usually, the formation of the grand coalition containing all players is assumed. A coalition acts like an individual and gains a payoff. The collective payoff of the coalition is allocated to the members. A payoff allocation achieved by players is a solution of a coalitional game. Shapley value, which was proposed by Lloyd Shapley [11], is a popular solution concept in coalitional games. Shapley value gives a unique payoff allocation which satisfies social rationality (Pareto efficiency) [12]. If a coalitional game satisfies superadditivity, Shapley value also satisfies individual rationality [12]. The individual rationality means that every player benefits from the coalition. This condition is necessary for the stability of the coalition. An interesting application of Shapley value is the Shapley-Shubik power index calculated by Lloyd Shapley and Martin Shubik [13]. They showed that Shapley value can be used to evaluate bargaining power of players.

This doctoral thesis introduces two game-theoretic models developed by the author: mosquito net game and cooperative emissions trading (CET) game. First, the mosquito net game is a non-cooperative game to understand why insecticide-treated nets (ITNs) distributed to malaria endemic areas were used for fishery and agriculture. The Nash equilibrium of the game suggests that alternative ITN use can be an individually rational strategy in low-income areas. Chapter 2 is devoted to the mosquito net game. Results from the two-player game were published in *Parasitology* [14], and the extension to the N-player game was published in *Journal of Theoretical Biology* [15]. Second, the CET game is a coalitional game to explain why international emissions trading under the Kyoto Protocol has suffered from low permit prices. By calculating Shapley value of the game, I demonstrated that a buyer can suppress permit price to a low level through bargaining with sellers. Chapter 3 is devoted to the CET game. As of January 2015, results from the CET game are unpublished.

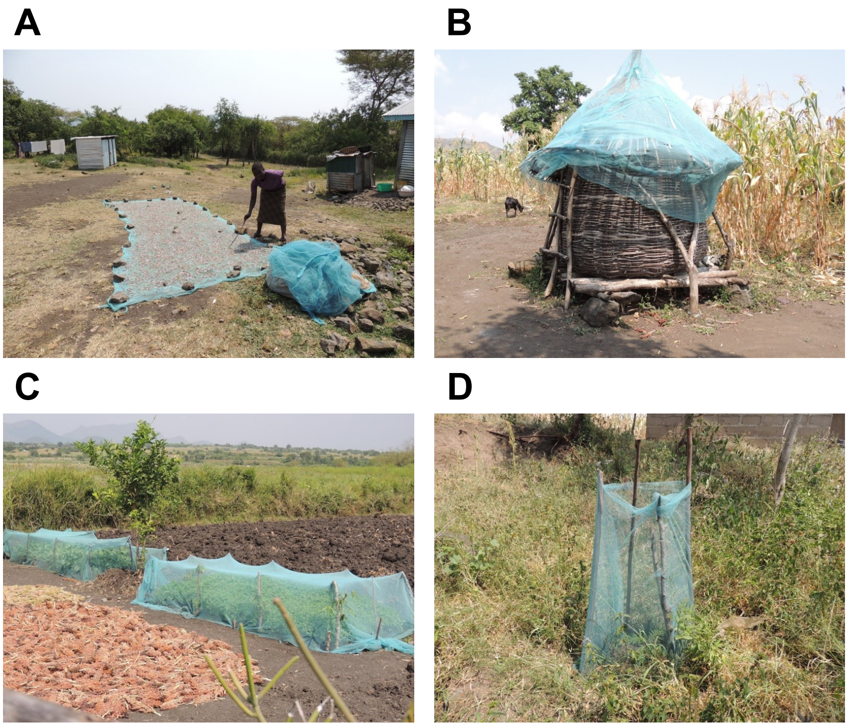

Figure 2.1: Alternative ITN uses observed in Kenya. ITNs are used for drying fish (Panel A) and protecting crops (Panels B–D). Photos were taken by Akiko Satake in July 2012.

Chapter 2

Non-cooperative Game for Malaria Prevention

2.1 Introduction

Malaria, transmitted by *Anopheles*, has threatened health of people living in tropical and subtropical areas. Social and economic damage from malaria is severe in sub-Saharan Africa. According to World Health Organization (WHO) [16], the number of malaria cases per 100,000 people was 38,424 in Guinea, 35,357 in Central African Republic, and 34,586 in Congo (point estimates for 2012). The costs for malaria prevention and treatment have hampered economic growth of the endemic countries [17].

In order to eliminate malaria, governmental and non-governmental organizations have distributed insecticide-treated nets (ITNs) to the endemic areas free of charge or at subsidized prices [16]. ITNs kill mosquitoes which contact the nets, and protect people sleeping inside the nets from mosquito bites. Several authors have reported that the distribution of ITNs contributed to the reduction of malaria deaths. In Kenya, an increase in ITN coverage from 7% to 67% resulted in a 44% reduction of mortality caused by malaria [18]. In Vanuatu in the South Pacific Ocean, the number of malaria cases was reduced by at least 50% when at most 20% of the population at risk was covered by ITNs [19]. The use of ITNs was effective for protection of children under five years old who are vulnerable to malaria [20].

However, some authors report that ITNs were used for economic activities such as fishery and agriculture. In major fishing villages in western Kenya, a considerable number of ITNs were used for catching and drying fish [21]. Figure 2.1 shows alternative ITN uses observed in Kenya. In Ethiopia, some people used ITNs for drying grain and tying cattle to a tree [22]. Similar ITN misuses were also observed in Timor-Leste in Southeast Asia [23]. These ITN misuses reduce public health benefits expected from ITN distribution. Why do people threatened by malaria use ITNs for alternative purposes? In order to understand this problem, I developed the mosquito net game, and analyzed decision making of ITN users.

2.2 Mosquito net game

2.2.1 Structure of the game

We consider a society formed by N players ($N \geq 2$). The set of players is $\mathbf{N} := \{1, 2, \ldots, N\}$. The society suffers from malaria, and each player is infected by malaria at probability P. If a player is infected by malaria, its labor productivity (income per capita) declines from L to zero. Suppose that ITNs are available free of charge. Each player chooses a strategy about the use of ITNs. The set of strategies is $\Sigma := \{\mathrm{T}, \mathrm{F}\}$. A player with strategy T uses ITNs for malaria prevention, and decreases its infection probability. A player with strategy F uses ITNs for economic activities, and increases its labor productivity. Let $\sigma_i \in \Sigma$ be the strategy of player $i \in \mathbf{N}$. A profile of strategies is written as $(\sigma_1, \sigma_2, \ldots, \sigma_N)$. The N-player mosquito net game has 2^N profiles.

For simplicity, we abbreviate a profile as (σ_i, m_{-i}). $m_{-i} \in \{0, 1, \ldots, N-1\}$ is the number of players with strategy T except player i. The infection probability of player i at a profile (σ_i, m_{-i}) is

$$p_i(\sigma_i, m_{-i}) := \begin{cases} \alpha_1 \alpha_2^{m_{-i}+1} P & (\sigma_i = \mathrm{T}) \\ \alpha_2^{m_{-i}} P & (\sigma_i = \mathrm{F}) \end{cases}, \tag{2.1}$$

where $\alpha_1 \in (0, 1)$ and $\alpha_2 \in (0, 1)$ denote individual and (per capita) community effects of ITNs, respectively. The individual effect decreases the infection probability for every player with strategy T by protecting it from mosquito bites [18–20]. The community effect decreases the infection probability for every player. Properly-used ITNs kill mosquitoes which contact the nets, and decrease the risk of malaria infection for the whole community [24–26]. Assume that the community effect intensifies as the number of proper ITN users increases. When $m \in \{0, 1, \ldots, N\}$ players have strategy T, the community effect of the whole society is α_2^m.

Table 2.1: Conditions for Nash equilibria of the N-player mosquito net game. $P_0 = (\beta - 1)/(\beta - \alpha_1\alpha_2)$, $P_k = P_0/\alpha_2^k$, and $k \in \{1, 2, \ldots, N-1\}$.

Type	Profile	Condition
All-F	$(\mathrm{F}, 0)$	$P \in [0, P_0]$
k-th degree free-rider	$(\mathrm{T}, k-1)$ and (F, k)	$P \in [P_{k-1}, P_k]$
All-T	$(\mathrm{T}, N-1)$	$P \in [P_{N-1}, 1]$

The labor productivity of player i at a profile (σ_i, m_{-i}) is

$$l_i(\sigma_i, m_{-i}) := \begin{cases} L & (\sigma_i = \mathrm{T}) \\ \beta L & (\sigma_i = \mathrm{F}) \end{cases}, \tag{2.2}$$

The parameter $\beta \in (1, \infty)$ represents the misuse effect of ITNs, which increases labor productivity of every player with strategy F.

The expected payoff of player i at a profile (σ_i, m_{-i}) is given by

$$\begin{aligned} U_i(\sigma_i, m_{-i}) &= p_i(\sigma_i, m_{-i}) \times 0 + (1 - p_i(\sigma_i, m_{-i})) \times l_i(\sigma_i, m_{-i}) \\ &= \begin{cases} (1 - \alpha_1\alpha_2^{m_{-i}+1}P)L & (\sigma_i = \mathrm{T}) \\ (1 - \alpha_2^{m_{-i}}P)\beta L & (\sigma_i = \mathrm{F}) \end{cases}. \end{aligned} \tag{2.3}$$

Each player chooses a strategy based on this payoff function.

2.2.2 Nash equilibrium

The Nash equilibrium is the set of profiles at which every player's strategy is the best response to other players' strategies [6, 7]. At a Nash equilibrium, no player has incentive to change its strategy. The N-player mosquito net game has three types of Nash equilibria: all-F, free-rider, and all-T. At the all-F (all-T) Nash equilibrium, every player has strategy F (strategy T). At the free-rider Nash equilibrium, k players have strategy T and other players have strategy F. The number $k \in \{1, 2, \ldots, N-1\}$ is called the degree of the free-rider Nash equilibrium. In economics, free riding means that someone benefits from goods or services provided by others without paying costs [1, 10]. At the free-rider Nash equilibrium, players with strategy F free ride on the community effect provided by players with strategy T. Table 2.1 shows the conditions for the Nash equilibria. The conditions are derived as follows.

The all-F profile is a Nash equilibrium if $U_i(\mathrm{F}, 0) \geq U_i(\mathrm{T}, 0)$. Solving this inequality with respect to P gives

$$P \in [0, P_0], \quad P_0 := \frac{\beta - 1}{\beta - \alpha_1\alpha_2}. \tag{2.4}$$

The k-th degree free-rider Nash equilibrium requires two inequalities. For player i with strategy T, $U_i(\mathrm{T}, k-1) \geq U_i(\mathrm{F}, k-1)$. For player j with strategy F, $U_j(\mathrm{F}, k) \geq U_j(\mathrm{T}, k)$. From these inequalities,

$$P \in [P_{k-1}, P_k], \quad P_k := \frac{P_0}{\alpha_2^k}. \tag{2.5}$$

The all-T profile is a Nash equilibrium if $U_i(\mathrm{T}, N-1) \geq U_i(\mathrm{F}, N-1)$. From this inequality,

$$P \in [P_{N-1}, 1], \quad P_{N-1} := \frac{P_0}{\alpha_2^{N-1}}. \tag{2.6}$$

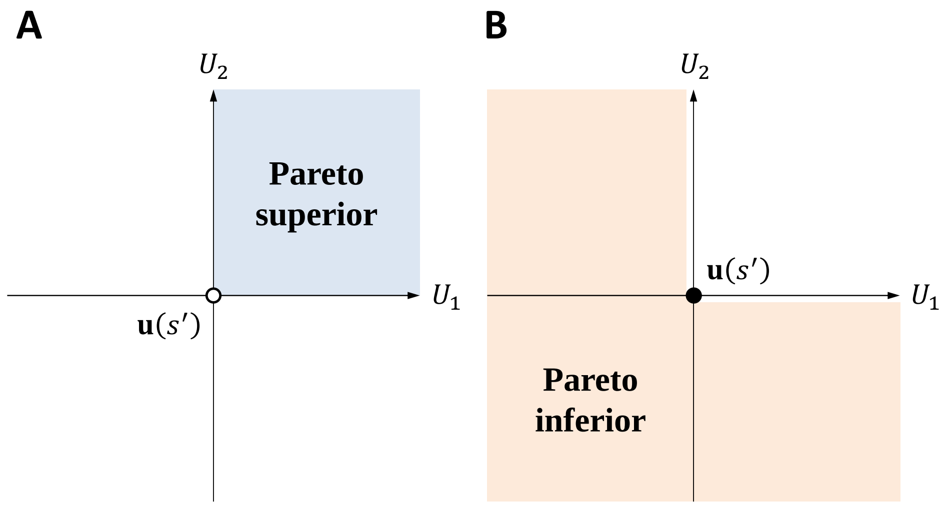

Figure 2.2: Pareto superior and inferior regions to a payoff vector $\mathbf{u}(s')$ ($N = 2$).

2.2.3 Pareto efficiency

A payoff allocation satisfies Pareto efficiency (Pareto optimality) if no player can increase its payoff without decreasing other player's payoff [1, 10, 12]. The Pareto efficiency means that the social benefit is allocated to the members with no loss. If the players of the mosquito net game are attracted to a Pareto efficient Nash equilibrium, the payoff allocation satisfies both individual and social rationality. A Pareto inefficient Nash equilibrium is a social dilemma, at which the players fail to achieve an efficient payoff allocation (e.g. the prisoner's dilemma [1, 5, 8, 9]).

Let $\mathbf{S} := \{(\sigma_1, \sigma_2, \ldots, \sigma_N) \mid \sigma_i \in \Sigma, i \in \mathbf{N}\}$ be the universal set of profiles. A profile $s^* \in \mathbf{S}$ is Pareto efficient if there is no profile $s \in \mathbf{S}$ such that $U_i(s) \geq U_i(s^*)$ for every player i and $U_j(s) > U_j(s^*)$ for a player j. This definition is rewritten as follows: A profile is Pareto efficient if the profile is Pareto inferior to all profiles. Let $\mathbf{u}(s) := (U_1(s), U_2(s), \ldots, U_N(s))$ be the payoff vector at a profile s. $\mathbf{u}(s)$ is Pareto superior to the payoff vector $\mathbf{u}(s')$ at a profile $s' \in \mathbf{S}$ if

$$\mathbf{u}(s) \in \mathbf{P}(s'), \quad \mathbf{P}(s') := \left(\prod_{i=1}^{N} [U_i(s'), \infty) \right) \setminus \{\mathbf{u}(s')\}, \tag{2.7}$$

where $\mathbf{P}(s')$ is the Pareto superior region to $\mathbf{u}(s')$. Panel A of Figure 2.2 shows $\mathbf{P}(s')$ in the case of $N = 2$. By moving from $\mathbf{u}(s')$ to $\mathbf{P}(s')$, at least one player can increase its payoff without decreasing other player's payoff. The complement of $\mathbf{P}(s')$ in the whole region $[0, \infty)^N$ is the Pareto inferior region

$$\mathbf{P}^C(s') := [0, \infty)^N \setminus \mathbf{P}(s'). \tag{2.8}$$

Panel B of Figure 2.2 shows $\mathbf{P}^C(s')$ in the case of $N = 2$. The shift from $\mathbf{u}(s')$ to $\mathbf{P}^C(s')$ maintains the payoff vector or decreases at least one player's payoff. A payoff vector $\mathbf{u}(s^*)$ is Pareto efficient if

$$\{\mathbf{u}(s) \mid s \in \mathbf{S}\} \subset \mathbf{P}^C(s^*). \tag{2.9}$$

All profiles are Pareto inferior to a Pareto efficient profile. The N-player mosquito net game has three types of Pareto efficiency: all-T, free-rider, and all-T. Table 2.2 shows the conditions for the Pareto efficient solutions. The conditions are derived as follows.

Table 2.2: Conditions for Pareto efficient solutions of the N-player mosquito net game. $P^*_0 = (\beta - 1)/(\beta - \alpha_1\alpha_2^N)$, $P^*_k = (\beta - 1)/(\alpha_2^k\beta - \alpha_1\alpha_2^N)$, and $k \in \{1, 2, \ldots, N-1\}$.

Type	Profile	Condition
All-F	$(\mathrm{F}, 0)$	$P \in [0, P^*_0]$
k-th degree free-rider	$(\mathrm{T}, k-1)$ and (F, k)	$P \in [0, P^*_k)$
All-T	$(\mathrm{T}, N-1)$	$P \in [P^*_0, 1]$

All-F Pareto efficiency

Let $\mathbf{S}_m \subset \mathbf{S}$, $m \in \{0, 1, \ldots, N\}$ be the set of profiles at which m players have strategy T. The all-F profile $s_0 = (\mathrm{F}, 0)$, which is the unique element of $\mathbf{S}_0$, is Pareto efficient if $\{\mathbf{u}(s) \mid s \in \mathbf{S}\} \subset \mathbf{P}^C(s_0)$. By the definition of Pareto inferiority (Figure 2.2), every profile is Pareto inferior to itself:

$$\mathbf{u}(s_0) \in \mathbf{P}^C(s_0). \tag{2.10}$$

The all-T profile $s_N = (\mathrm{T}, N-1)$, which is the unique element of $\mathbf{S}_N$, is Pareto inferior to the all-F profile if $U_i(\mathrm{F}, 0) \geq U_i(\mathrm{T}, N-1)$. From this inequality,

$$\mathbf{u}(s_N) \in \mathbf{P}^C(s_0) \leftrightarrow P \in [0, P^*_0], \quad P^*_0 := \frac{\beta - 1}{\beta - \alpha_1\alpha_2^N}. \tag{2.11}$$

Under this condition, all free-rider profiles are Pareto inferior to the all-F profile. $\mathbf{S}_k$ contains free-rider profiles with degree $k \in \mathbf{K} := \{1, 2, \ldots, N-1\}$. At a k-th degree free-rider profile $s_k \in \mathbf{S}_k$, k players have strategy T, and other players have strategy F. The profiles for T-player and F-player are $(\mathrm{T}, k-1)$ and (F, k), respectively. Since $U_i(\mathrm{F}, 0) < U_i(\mathrm{F}, k)$, the inequality $U_i(\mathrm{F}, 0) > U_i(\mathrm{T}, k-1)$ is necessary for the Pareto inferiority of s_k to s_0. Under the condition (2.11), $U_i(\mathrm{F}, 0) \geq U_i(\mathrm{T}, N-1) > U_i(\mathrm{T}, k-1)$. Hence

$$\forall k \left(P \in [0, P^*_0] \to \{\mathbf{u}(s_k) \mid s_k \in \mathbf{S}_k\} \subset \mathbf{P}^C(s_0)\right). \tag{2.12}$$

All profiles are Pareto inferior to the all-F profile if $P \in [0, P^*_0]$.

Free-rider Pareto efficiency

Every k-th degree free-rider profile is Pareto efficient if $\{\mathbf{u}(s) \mid s \in \mathbf{S}\} \subset \mathbf{P}^C(s_k)$. Free-rider profiles with the same degree are Pareto inferior to each other. Suppose that the players shift from s_k to $s'_k \in \mathbf{S}_k$. If $s_k = s'_k$, the payoff vector does not change. If $s_k \neq s'_k$, at least one player changes its strategy. The number of players switching from T to F is equal to the number of players switching from F to T. If a player increases its payoff by switching from T to F, there exists a player which decreases its payoff by switching from F to T. Thus the shift from s_k to s'_k maintains the payoff vector or decreases at least one player's payoff:

$$\forall k \, \forall s_k \left(\{\mathbf{u}(s'_k) \mid s'_k \in \mathbf{S}_k\} \subset \mathbf{P}^C(s_k)\right). \tag{2.13}$$

Since $U_i(\mathrm{F}, k) > U_i(\mathrm{F}, 0)$, the all-F profile is Pareto inferior to all free-rider profiles:

$$\forall k \, \forall s_k \left(\mathbf{u}(s_0) \in \mathbf{P}^C(s_k)\right). \tag{2.14}$$

Suppose that the players shift from a k-th degree free-rider profile to the all-T profile. In this case, $(N-k)$ players switch from F to T, and other players hold T. Since

$U_i(\mathrm{T}, k-1) < U_i(\mathrm{T}, N-1)$, the inequality $U_i(\mathrm{F}, k) > U_i(\mathrm{T}, N-1)$ is necessary for the Pareto inferiority of s_N to s_k. From this inequality,

$$\forall k\, \forall s_k \left(\mathbf{u}(s_N) \in \mathbf{P}^C(s_k) \leftrightarrow P \in [0, P_k^*)\right), \tag{2.15}$$

where

$$P_k^* := \frac{\beta - 1}{\alpha_2^k \beta - \alpha_1 \alpha_2^N}.$$

Finally, we consider the case where the players shift from a k-th degree free-rider profile to free-rider profiles with a different degree $l \in \mathbf{L} := \{1, 2, \dots, k-1, k+1, \dots, N-1\}$. If $l < k$, at least one player holds its strategy, or every player changes its strategy. In the former case, at least one player decreases its payoff because of $U_i(\mathrm{T}, k-1) > U_i(\mathrm{T}, l-1)$ and $U_i(\mathrm{F}, k) > U_i(\mathrm{F}, l)$. In the latter case, no player can increase its payoff without decreasing other player's payoff. If $k < l$, at least one player switches from F to T. Under the condition (2.15), $U_i(\mathrm{F}, k) > U_i(\mathrm{T}, N-1) > U_i(\mathrm{T}, l-1)$, and the switch from F to T decreases the player's payoff. Hence

$$\forall k\, \forall s_k\, \forall l \left(P \in [0, P_k^*) \rightarrow \{\mathbf{u}(s_l) \mid s_l \in \mathbf{S}_l\} \subset \mathbf{P}^C(s_k)\right). \tag{2.16}$$

All profiles are Pareto inferior to every k-th degree free-rider profile if $P \in [0, P_k^*)$.

All-T Pareto efficiency

The all-T profile is Pareto efficient if $\{\mathbf{u}(s) \mid s \in \mathbf{S}\} \subset \mathbf{P}^C(s_N)$. Similar to Eq. (2.10),

$$\mathbf{u}(s_N) \in \mathbf{P}^C(s_N). \tag{2.17}$$

Since $U_i(\mathrm{T}, N-1) > U_i(\mathrm{T}, k-1)$, the shift from s_N to s_k decreases at least one player's payoff. Hence all free-rider profiles are Pareto inferior to the all-T profile:

$$\forall k \left(\{\mathbf{u}(s_k) \mid s_k \in \mathbf{S}_k\} \subset \mathbf{P}^C(s_N)\right), \tag{2.18}$$

The all-F profile is Pareto inferior to the all-T profile if $U_i(\mathrm{T}, N-1) \geq U_i(\mathrm{F}, 0)$. From this inequality,

$$\mathbf{u}(s_0) \in \mathbf{P}^C(s_N) \leftrightarrow P \in [P_0^*, 1]. \tag{2.19}$$

All profiles are Pareto inferior to the all-T profile if $P \in [P_0^*, 1]$.

2.3 Results and discussion

2.3.1 Individual and social rationality in ITN misuse

From Tables 2.1 and 2.2, the conditions for Pareto efficient Nash equilibria (PNE) and social dilemmas (SDs) are derived (Table 2.3). The distribution of the solutions is illustrated as Figure 2.3. As the infection probability (P) increases, the Nash equilibrium shifts from all-F to free-rider, and then shifts to all-T. If the infection probability is lower than P_0, the benefit from alternative ITN use exceeds the damage from malaria infection, and all players use ITNs for economic activities. If the infection probability lies between P_{k-1} and P_k, $(N-k)$ players switch from strategy F to strategy T, and use ITNs for malaria prevention. The other players free ride on the community effect provided by the

Table 2.3: Conditions for Pareto efficient Nash equilibria (PNE) and social dilemmas (SDs) of the N-player mosquito net game.

Solution	Condition
All-F PNE	$P \in [0, P_0^*]$
All-F SD	$P \in (P_0^*, P_0]$
k-th degree free-rider PNE	$P \in [P_{k-1}, P_k^*)$
k-th degree free-rider SD	$P \in [P_k^*, P_k]$
All-T PNE	$P \in [P_{N-1}, 1]$
All-T SD	$P \in \varnothing$

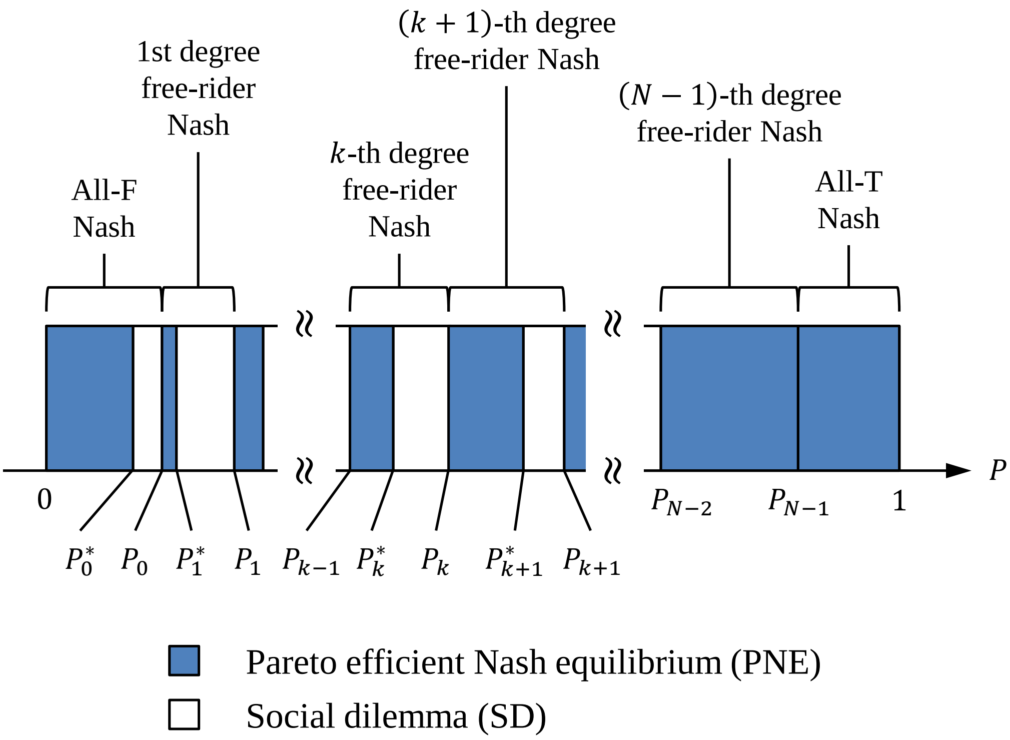

Figure 2.3: Distribution of PNE and SDs of the N-player mosquito net game. The number of players with strategy T (degree k) increases as the infection probability (P) increases. P_k^* approaches P_k as k approaches $N-1$. The $(N-1)$-th degree free-rider Nash equilibrium is Pareto efficient except at the right-side edge $P = P_{N-1}$. The all-T Nash equilibrium is always Pareto efficient.

proper ITN users. If the infection probability is higher than P_{N-1}, the risk of malaria infection is high, and all players use ITNs for malaria prevention. The distribution of Nash equilibria indicates that alternative ITN use can be an individually rational strategy. The region of the all-F Nash equilibrium always exists inside the domain $[0, 1]$. Meanwhile, the region of the all-T Nash equilibrium is pushed out of the domain $[0, 1]$ if α_2 is sufficiently small (i.e., if the community effect is sufficiently strong). In this case, at least one player misuses ITNs regardless of the infection probability. A strong community effect benefits free riders. Therefore ITNs may be used for alternative purposes even if the infection probability is high.

Surprisingly, alternative ITN use can be a socially rational strategy. The all-F Nash equilibrium is Pareto efficient if the infection probability is lower than P_0^*. The k-th degree

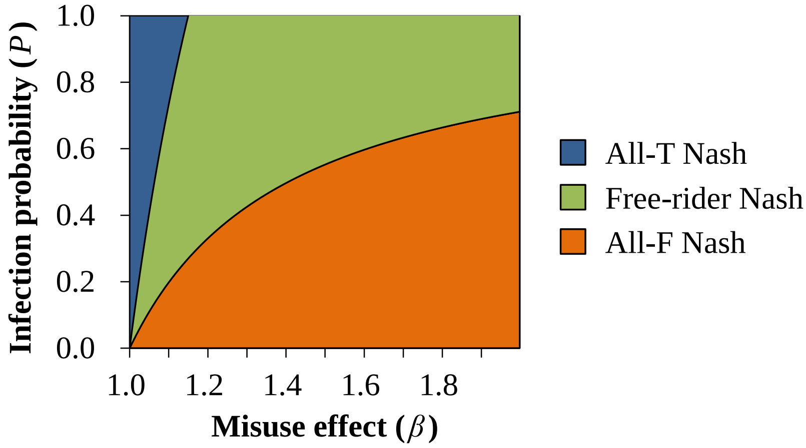

Figure 2.4: Distribution of Nash equilibria of the N-player mosquito net game ($\alpha_1 = 0.6$, $\alpha_2 = 0.99$, $N = 100$). A higher misuse effect means a lower labor productivity.

free-rider Nash equilibrium is Pareto efficient if the infection probability lies between P_{k-1} and P_k^*. If the players are attracted to these solutions, alternative ITN use satisfies both individual and social rationality. The all-F Nash equilibrium loses Pareto efficiency if the infection probability is higher than P_0^*. In the region of the all-F social dilemma, the all-T profile is Pareto efficient, but the players are attracted to the all-F profile. If the infection probability lies between P_k^* and P_k, the players are attracted to the k-th free-rider social dilemma. The length of the interval $[P_k^*, P_k]$ is

$$P_k - P_k^* = \frac{\alpha_1 \alpha_2 P_0 P_k^* (1 - \alpha_2^{N-k-1})}{(\beta - 1)}, \tag{2.20}$$

which approaches zero as degree k approaches $N-1$. Hence the $(N-1)$-th degree free-rider Nash equilibrium is Pareto efficient except at the right side edge $P = P_{N-1}$. In a society containing more than two players, free riding may lead to an inefficient payoff allocation. The all-T Nash equilibrium is always Pareto efficient.

2.3.2 Poverty and ITN misuse

Malaria is called a disease of poverty. As pointed out by Sachs and Malaney [17], most of the malaria endemic areas are located in low-income developing countries. This observation is explained by a positive feedback between poverty and malaria. Poverty promotes malaria transmission by limited expenditures on malaria prevention and treatment, and social and economic damage caused by malaria accelerate poverty. Is there any relationship between poverty and ITN misuse? From the mosquito net game, I found that low labor productivity encourages people to use ITNs for economic activities.

Labor productivity (L) has no direct impact on the distribution of the solutions, but indirectly influences it through the misuse effect (β). Let $\Delta L \in [0, \infty)$ be extra income from alternative ITN use. Assume that ΔL is independent of labor productivity. By the definition of the misuse effect,

$$\beta := \frac{L + \Delta L}{L} = 1 + \frac{\Delta L}{L} \propto L^{-1}. \tag{2.21}$$

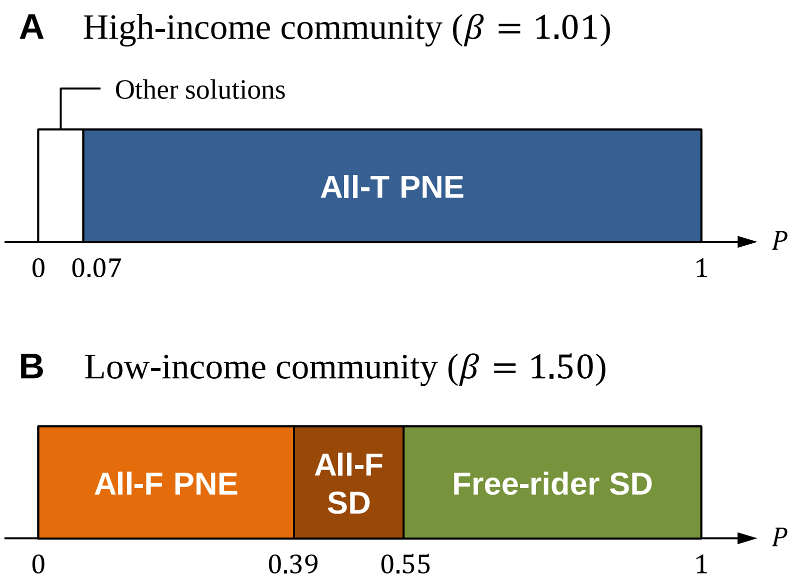

Figure 2.5: Distributions of PNE and SDs in high-income and low-income communities ($\alpha_1 = 0.6$, $\alpha_2 = 0.99$, $N = 100$). The high-income community has a weak misuse effect ($\beta = 1.01$), and the low-income community has a strong misuse effect ($\beta = 1.50$).

The misuse effect is proportional to the inverse of labor productivity. Therefore low-income and high-income countries are characterized by high and low values of β, respectively.

The number of proper ITN users decreases as the misuse effect increases (Figure 2.4). If the misuse effect is weak (i.e. $\beta \approx 1$), ITN use for malaria prevention is an individually rational strategy, and the all-T Nash equilibrium holds regardless of the infection probability (P). As β increases, extra income from ITN misuse increases, and ITN use for economic activities can be an individually rational strategy. If the misuse effect is sufficiently strong (i.e. $\beta \gg 1$), the all-F or free-rider Nash equilibrium holds regardless of the infection probability.

In a high-income community, the extra income ΔL is negligible compared with each player's labor productivity, and the misuse effect is weak. The benefit from alternative ITN use cannot offset the damage from malaria infection. Therefore every player uses ITNs for malaria prevention even if the infection probability is low. The all-T Nash equilibrium is always Pareto efficient, and proper ITN use contributes to an efficient payoff allocation. In a low-income community, however, the extra income ΔL is attractive for the players, and the misuse effect is strong. As a result, at least one player uses ITNs to enhance its labor productivity even if the infection probability is high. ITN misuse is not always Pareto efficient, and the players may face with a social dilemma (Figure 2.5, see also Appendix A).

2.3.3 Human population size and ITN misuse

The distribution of Nash equilibria is influenced by human population size (the number of players, N). The region of the k-th degree free-rider Nash equilibrium exists inside the domain $[0, 1]$ if $P_{k-1} \in [0, 1]$. From this condition, we obtain the maximum degree of the

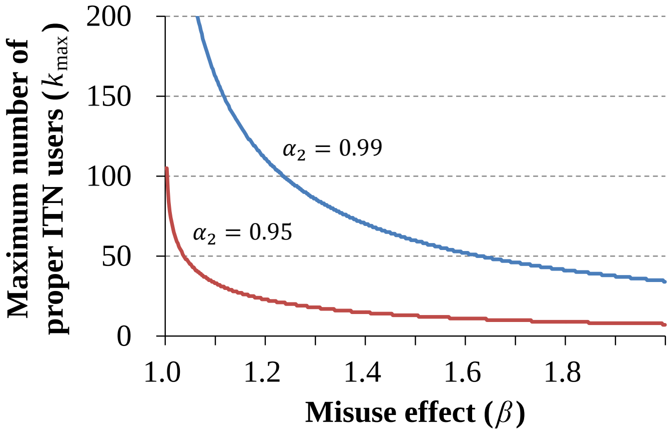

Figure 2.6: Maximum number of proper ITN users ($k_{\max}$). The individual effect (α_1) and the infection probability (P) are fixed at 0.6 and 0.8, respectively.

free-rider Nash equilibrium:

$$k_{\max} := \operatorname{floor}\left(1 + \frac{\log P_0}{\log \alpha_2}\right), \tag{2.22}$$

where floor(x) gives the largest integer not greater than x. This result indicate that the maximum number of proper ITN users is limited by the individual, community, and misuse effects of ITNs (Figure 2.6). For instance, a community with $(\alpha_1, \alpha_2, \beta) = (0.6, 0.99, 1.5)$ has $k_{\max} = 60$. If the community contains 50 players, the all-T Nash equilibrium is achieved under a sufficiently high infection probability. If the community contains 100 players, however, the free-rider Nash equilibria with degrees higher than 60 and the all-T Nash equilibrium are pushed out of the domain $[0, 1]$. Even if the infection probability is extremely high (e.g. $P = 1$), at most 60 players use ITNs for malaria prevention. The realization of the all-T Nash equilibrium would be difficult in a large society.

2.3.4 Economic regulation of ITN misuse

The all-T Nash equilibrium is desirable from the viewpoint of public health. However, ITN misuse is an individually rational strategy in low-income areas. This mismatch between public-health and individual benefits is interpreted as a social dilemma. If the players are attracted to the all-F or free-rider Nash equilibrium, they cannot reach the all-T Nash equilibrium without external forcing. Here I demonstrate that the all-T Nash equilibrium is achieved if a tax is imposed on extra income from ITN misuse. Taxation provides people with an incentive to change their strategies, and help them escape from a social dilemma [1, 9, 27].

Suppose that the players with strategy F are forced to pay a tax. Let $r \in [0, 1]$ be a tax rate. The expected payoff inclusive of tax is

$$U_i^{\text{tax}}(\sigma_i, m_{-i}) := \begin{cases} U_i(\sigma_i, m_{-i}) & (\sigma_i = \text{T}) \\ (1 - r)U_i(\sigma_i, m_{-i}) & (\sigma_i = \text{F}) \end{cases}. \tag{2.23}$$

The strict all-T Nash equilibrium holds if $U_i^{\text{tax}}(\text{T}, N-1) > U_i^{\text{tax}}(\text{F}, N-1)$. Solving this

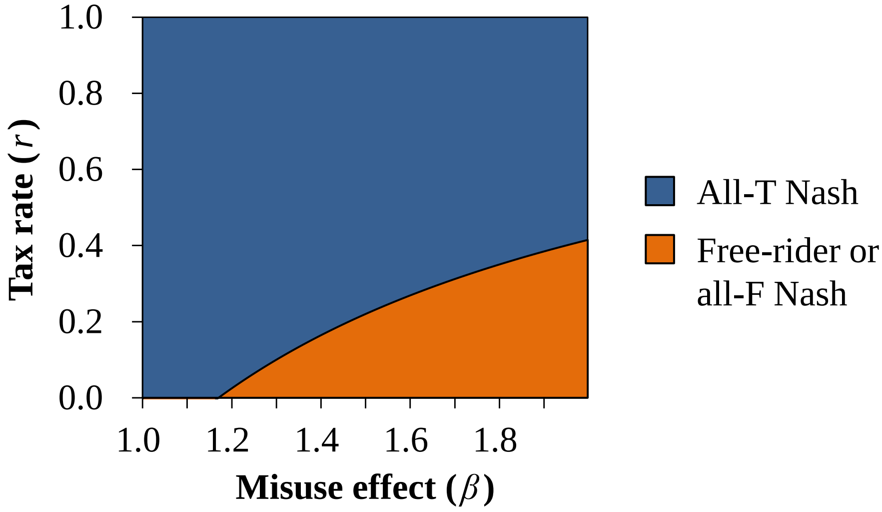

Figure 2.7: Distribution of the Nash equilibria under a tax on improper ITN users ($\alpha_1 = 0.6$**,** $\alpha_2 = 0.99$**,** $N = 100$**,** $P = 0.8$**).** The border between the all-T Nash equilibrium and other solutions is given by $r^* = 1 - U_i(\mathrm{T}, N-1)/U_i(\mathrm{F}, N-1)$.

inequality with respect to r gives

$$r > r^* := 1 - \frac{U_i(\mathrm{T}, N-1)}{U_i(\mathrm{F}, N-1)}, \tag{2.24}$$

where r^* is the rate of payoff increase caused by the shift from the all-T profile to the $(N-1)$-th degree free-rider profile. If $U_i(\mathrm{T}, N-1) > U_i(\mathrm{F}, N-1)$, the all-T Nash equilibrium is automatically achieved, and the tax is unnecessary. If $U_i(\mathrm{T}, N-1) \leq U_i(\mathrm{F}, N-1)$, the players are attracted to the all-T Nash equilibrium at a tax rate $r > r^*$ (Figure 2.7). In a high-income community characterized by a low β, extra income from ITN misuse is negligible, and the all-T Nash equilibrium holds without the tax. In a low-income community characterized by a high β, extra income from ITN misuse is attractive for the players, and a high tax rate is necessary to eliminate ITN misuse.

2.4 Summary and Conclusion

Developing countries in tropical and sub-tropical areas have suffered from social and economic damage caused by malaria transmission. Insecticide-treated nets (ITNs) have been distributed to malaria endemic areas, which contributed to the reduction of malaria deaths. Meanwhile, some ITNs were used for economic activities such as fishery and agriculture. In this study, I developed a non-cooperative game (called mosquito net game) to understand why people threatened by malaria use ITNs for alternative purposes. From Nash equilibria of the mosquito net game, I found that alternative ITN use can be an individually rational strategy. In a high-income community, an additional benefit from ITN misuse is negligible compared to each player's income. Therefore all players use ITNs for malaria prevention even if the infection probability is low. In a low-income community, however, an additional benefit from ITN misuse exceeds the damage from malaria infection. As a result, many players are attracted to ITN misuse even if the infection probability is high. This result suggests that poverty is an important factor behind ITN misuse. Alternative ITN use is not desirable from the viewpoint of Pareto efficiency. A community containing improper ITN users may face with a social dilemma. Self-interest individuals have no incentive to change their strategies, and cannot escape from a social dilemma without external forcing. I demonstrated that ITN misuse can be eliminated by imposing a tax on improper ITN users. The tax reduces benefits from ITN misuse and free riding, and encourages the players to use ITNs for malaria prevention. If all players choose the proper ITN use, the payoff allocation satisfies both individual and social rationality. An efficient payoff allocation is achieved under an adequate tax rate.

Appendix A

The k-th free-rider Nash equilibrium can be Pareto efficient if $P_k^* \in [P_{k-1}, P_k]$. From this condition, we obtain the minimum degree of the free-rider PNE:

$$k^*_{\min} := \text{ceiling}\left(N + 1 - \frac{\log(\alpha_2 - (1-\alpha_2)\beta/\alpha_1)}{\log \alpha_2}\right), \quad \beta < \frac{\alpha_1 \alpha_2}{1-\alpha_2}, \tag{2.25}$$

where ceiling(x) gives the smallest integer not less than x. In Panel B of Figure 2.5, $k^*_{\min} = 98$. Only the 98th and 99th degree free-rider Nash equilibria can be Pareto efficient. The maximum degree of the free-rider Nash equilibrium ($k_{\max}$) is 60 (Figure 2.6). Therefore the free-rider Nash equilibria contained by the domain $[0, 1]$ are social dilemmas. Note that every degree free-rider Nash equilibrium can be Pareto efficient if $\beta \geq \alpha_1\alpha_2/(1-\alpha_2)$.

Chapter 3

Cooperative Game for International Emissions Trading

3.1 Introduction

Scientific evidence clearly indicates that climate change is driven by greenhouse gases (mainly carbon dioxide, CO_2) emitted from human activities [28]. Rapid reduction of anthropogenic CO_2 emissions is required to protect present and future generations from disastrous impacts of climate change [29–32]. The United Nations Framework Convention on Climate Change (UNFCCC) agreed the Kyoto Protocol in 1997, and decided to reduce CO_2 emissions from Annex B Parties to the levels in 1990 [33, 34]. The Kyoto Protocol introduced international emissions trading (IET) to accelerate emission reduction. Each country possesses marketable emission permits equivalent to its emission cap specified in the Kyoto Protocol. Countries facing permit shortfalls must purchase permits from other countries. The cost for acquiring additional permits provides buyers with an incentive to reduce their emissions. The basic competitive model in economics shows that emissions trading is a cost-effective way of controlling CO_2 emissions [1, 9, 10, 27, 35].

The Kyoto Protocol completed the first commitment period (CP1) in 2012. The international permit market under CP1 was far from an efficient market drawn by the basic competitive model. The annual average price of permits (assigned amount units, AAUs) peaked at US$12.92 per ton of CO_2 in 2009, and then rapidly declined to US$6.77 in 2011 [36–38]. Even much lower prices were reported in 2012 [39]. These prices are relatively low compared to many estimates of the social cost of carbon (SCC, marginal damage caused by an additional ton of CO_2 emissions) [40, 41]. A permit price lower than the SCC implies that the risks of climate change are underestimated. Since buyers can acquire additional permits at low costs, the emissions reduction may not reach the optimal level.

The downward trend in permit price is attributed to the deficiencies of the Kyoto Protocol, which have been discussed by many authors. First, the Kyoto Protocol has no strict sanctions against non-participation and non-compliance [43, 44]. In Marrakesh Accords, the Kyoto Protocol introduced some non-financial sanctions against non-compliance [45]. However, a non-compliant country can avoid the sanctions by withdrawing from the Kyoto Protocol. The Kyoto Protocol depending on voluntary actions of the members is vulnerable to free riding. If a buyer loses the willingness to purchase permits, it can withdraw from the market without paying costs. In fact, the international permit market has experienced non-participation or non-compliance of major buyers: the US, Canada,

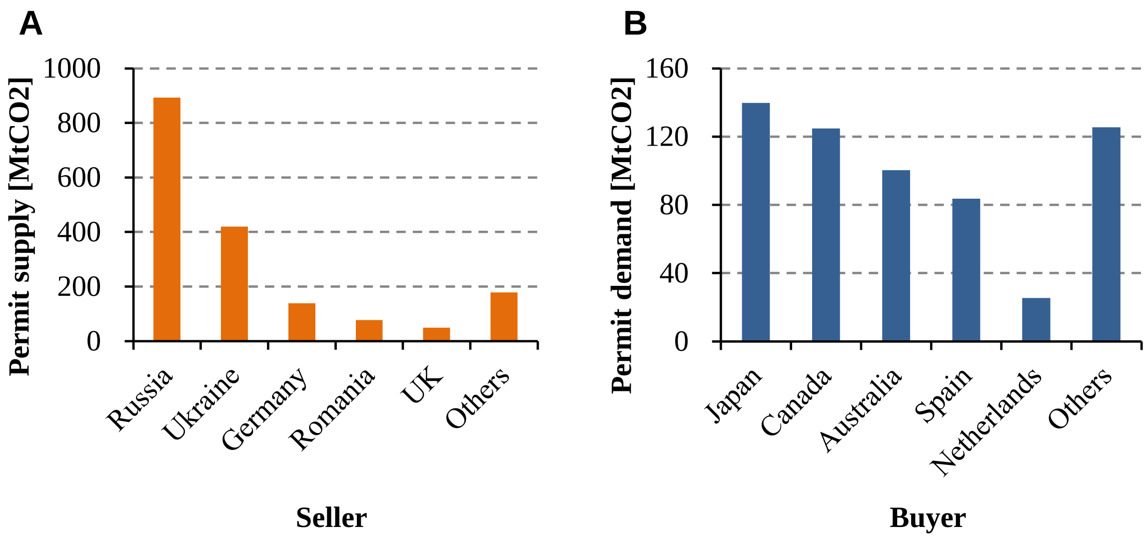

Figure 3.1: Permit supply and demand in Annex B Parties (annual average, 2008–2012). Calculated by the author from CO_2 emission data [42] and the Quantified Emission Limitation or Reduction Commitment (QELRC) of the Kyoto Protocol [33]. The US and the EU bubble are not included. Let G be annual average emissions from a country between 2008 and 2012, and let C be the emission cap (per year) of the country specified in the Kyoto Protocol. (A) If $G < C$, the country is a seller with a supply of $C - G$. (B) If $C < G$, the country is a buyer with a demand of $G - C$.

and Japan [46–48]. The absence of major buyers leads to a smaller demand and a lower price. Moreover, the right of buyers to withdraw from the market is a threat to sellers. If major buyers exercise the right, sellers cannot gain benefits from emissions trading. Therefore sellers are forced to provide permits at low prices which are acceptable to buyers.

Second, the allocation of permits to transition economies (specifically Russia and Ukraine) was too generous [10, 34]. Due to the hot air, the IET under CP1 has suffered from the oversupply of permits (Figure 3.1). The withdrawal of the US from the Kyoto Protocol accelerated the oversupply of permits. If the US participated in the IET, it would have been the largest buyer with a demand of 876 $MtCO_2$ per year [42]. Several authors estimate the impacts of the US withdrawal on permit price using computational models [49–54]. The 2008–2009 global financial crisis widened the supply-demand gap (Figure 3.2). In 2009, CO_2 emissions from Annex B Parties decreased in response to the economic downturn [42]. As a result, the demand-side permit shortfall decreased, while the supply-side permit surplus increased. The vulnerable market under CP1 has been sustained by Japan's purchasing power [36–39].

These observations suggest that the international permit market under CP1 was a buyer's market. In a buyer's market, at least one buyer exercises market power to manipulate price. The cost-effective performance of emissions trading assumes a competitive market with no price maker [55]. If there exists a price maker in the market, emissions trading may fail to achieve the optimal price [56] (see [35] for the extensions of this result). In the context of the IET under the Kyoto Protocol, many authors have investigated market power of sellers, especially transition economies. By extending Hahn's model [56], Maeda [57] concludes that sellers can exercise market power by forming a cartel but buyers cannot. The impacts of seller cartels on permit price are estimated by computational models [50–52, 54]. However, Godal and Meland [58] demonstrate that

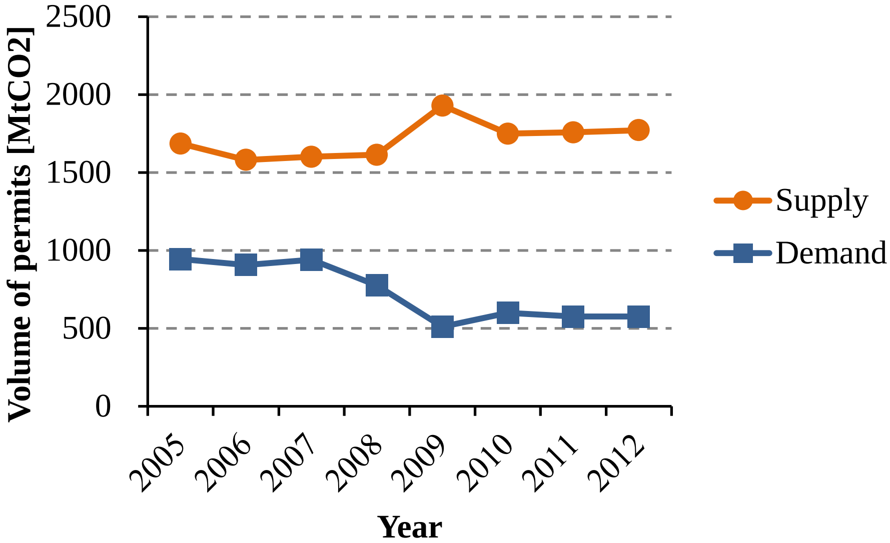

Figure 3.2: Aggregate permit supply and demand in Annex B Parties, 2005–2012. Calculated by the author from CO_2 emission data [42] and the QELRC of the Kyoto Protocol [33]. The US is not included.

the formation of a seller cartel is not a dominant strategy for sellers. Strategic behavior of buyers may nullify benefits from a seller cartel. Moreover, they show that a coalition containing both buyers and sellers is profitable. Under the Kyoto Protocol, sellers must cooperate with buyers to gain benefits from emissions trading. Permit prices are determined by bargaining. In order to understand the IET under CP1, we need to evaluate power relationships between buyers and sellers.

Game theory is a useful tool to solve bargaining problems. There are two types of approaches: non-cooperative and cooperative. Non-cooperative games focus on how self-interest players form a stable coalition. Strategic behavior of players is described by solution concepts satisfying individual rationality (e.g. max-min solution and Nash equilibrium). The non-cooperative approach has been applied to international climate negotiations [59–66]. In contrast, cooperative games (coalitional games) focus on how benefits from a coalition are allocated to the members [4, 12, 67]. A payoff allocation is determined by solution concepts satisfying both individual and social rationality (e.g. core and Shapley value). The solution concepts for cooperative games are associated with bargaining power of players. The cooperative approach has been applied to the allocation of natural and environmental resources [68–71].

In this chapter, I develop a coalitional game of the IET, and demonstrate that buyers have dominant bargaining power under the Kyoto Protocol. In my model, called cooperative emissions trading (CET) game, a buyer purchases permits from sellers only if the buyer forms a coalition with the sellers. In the real market, several buyers may cooperate with each other. For simplicity, however, coalitions containing more than one buyer (multi-buyer coalitions) are not considered in the CET game. The focus of this game is bargaining between each buyer and sellers (see Future Research for the multi-buyer CET game). It is assumed that a buyer gains benefits from a coalition with sellers. If compliance enforcement is weak, self-interest buyers withdraw from the market without purchasing permits. However, political and economic benefits from international cooperation encourage buyers to participate in the market. The benefits from a coalition are interpreted as ancillary benefits of the IET [64, 72]. Under these assumptions, the CET

Table 3.1: Characteristic function v

Type	Coalition N	Collective payoff $v(N)$
Empty	$\varnothing$	0
Buyer	$\mathbf{B}$	0
Seller	$S_+ \subseteq \mathbf{S} \setminus \varnothing$	0
Normal	$\mathbf{B} \cup S_+$	$\lambda Q_{\mathbf{B}\cup S_+}$

game has a superadditive characteristic function. The collective payoff of the coalition, which is equal to the value of ancillary benefits for the buyer, is allocated to the members by Shapley value [11, 12, 67]. Shapley value gives a unique payoff allocation satisfying social rationality (Pareto efficiency). Shapley value also satisfies individual rationality for superadditive games. Shapley value can be used as an index of bargaining power (e.g. Shapley-Shubik index [13]). Using Shapley value, I evaluate the supply-side and demand-side bargaining power. Permit price is derived from the buyer's Shapley value, which is a function of the demand-side bargaining power. The payoff allocation based on another solution concept (propensity to disrupt [73]) is shown in Future Research.

3.2 Analysis

The CET game is a coalitional game with a buyer and s-sellers ($s \geq 1$). Let $\mathbf{B} := \{-1\}$ be the set of a buyer, and let $\mathbf{S} := \{1, 2, \ldots, s\}$ be the set of sellers. The set of players is $\mathbf{N} := \mathbf{B} \cup \mathbf{S}$. Each player $i \in \mathbf{N}$ has C_i (tCO_2) of permits in advance. Assume $C_{-1} < 0$ for the buyer and $C_j > 0$ for any seller $j \in \mathbf{S}$. A player can form a coalition with other players. A coalition $N \subseteq \mathbf{N}$ is a subset of the player set, and the CET game has 2^{s+1} coalitions. The coalitions are classified into four types (Table 3.1). The empty coalition $\varnothing$ is the empty set. The buyer coalition $\mathbf{B}$ is the buyer set, and a seller coalition $S_+ \subseteq \mathbf{S} \setminus \varnothing$ is a non-empty seller set. A normal coalition, denoted by $\mathbf{B} \cup S_+$, contains the buyer and at least one seller. Permit demand and supply in $\mathbf{B} \cup S_+$ are $|C_{-1}|$ and $\Gamma_{S_+} := \sum_{j \in S_+} C_j$, respectively.

3.2.1 Payoff Functions

A player's payoff is determined by the coalition in which the player participates. The buyer's payoff function is

$$U_{-1}(N) := \begin{cases} (\lambda - P) Q_{\mathbf{B}\cup S_+} & \text{if } \; N = \mathbf{B} \cup S_+ \\ 0 & \text{otherwise} \end{cases}. \tag{3.1}$$

P is permit price per ton of CO_2 emissions ($P > 0$). $Q_{\mathbf{B}\cup S_+} := \min\{|C_{-1}|, \Gamma_{S_+}\}$ is the volume of permits transferred from a seller coalition S_+ to the buyer. The buyer's willingness-to-pay (WTP), denoted by λ, is the maximum permit price that the buyer is willing to pay ($\lambda \geq 0$). If a normal coalition $\mathbf{B} \cup S_+$ is formed, the buyer pays $PQ_{\mathbf{B}\cup S_+}$ for permits, and receives $\lambda Q_{\mathbf{B}\cup S_+}$ from the coalition. $\lambda Q_{\mathbf{B}\cup S_+}$ is equal to the value of the coalition for the buyer. The j-th seller's payoff function is

$$U_j(N) := \begin{cases} P q_j & \text{if } \; N = \mathbf{B} \cup S_+ \; \text{ and } \; j \in S_+ \\ 0 & \text{otherwise} \end{cases}. \tag{3.2}$$

q_j is the volume of permits transferred from seller j to the buyer, which satisfies $\sum_{j \in S_+} q_j = Q_{\mathbf{B} \cup S_+}$.

3.2.2 Characteristic Function

The collective payoff of a coalition is given by the characteristic function

$$v(N) := \sum_{i \in N} U_i(N). \tag{3.3}$$

The collective payoff can be positive only in normal coalitions (Table 3.1). v is a superadditive function which satisfies $v(N_0) + v(N_1) \leq v(N_0 \cup N_1)$ for any two coalitions N_0 and N_1 such that $N_0 \cap N_1 = \varnothing$. The collective payoff monotonically increases as the coalition size $|N|$ increases. Hence the formation of the grand coalition $\mathbf{N}$ is expected. The CET game is the problem of how to allocate $v(\mathbf{N}) = \lambda Q_{\mathbf{N}}$ to players.

The grand coalition is stable only if every player receives a non-negative payoff from it. If the payoff allocation to player i is negative, the player withdraws from the grand coalition and gains a zero payoff from the single coalition $\{i\}$. From $U_{-1}(\mathbf{N}) \geq 0$ and $P > 0$, we obtain the condition for individual rationality:

$$0 < P \leq \lambda. \tag{3.4}$$

Only if the buyer has a positive WTP, permit price can be positive, and every player receives a non-negative payoff. If the buyer has a zero WTP, the grand coalition collapses, and every player receives a zero payoff.

Proposition 1 *Permit price can be positive only if there exists a buyer with a positive WTP in the market.*

3.2.3 Shapley Value

Shapley value gives a unique payoff allocation which satisfies social rationality (Pareto efficiency) [11, 12, 67]. Since the characteristic function v is superadditive, Shapley value of the CET game also satisfies individual rationality (Eq. (3.4)).

Let $\mathbf{M}$ be the set of $(s+1)!$ permutations of $(s+1)$ players. A permutation

$$m = (m(1), m(2), \dots, m(k), \dots, m(s+1)) \in \mathbf{M} \tag{3.5}$$

indicates the order in which each player forms a coalition. Player $m(1)$ forms the single coalition $\{m(1)\}$. Player $m(2)$ joins $\{m(1)\}$, and forms the two-player coalition $\{m(1), m(2)\}$. Player $m(k)$ forms the k-player coalition $\{m(1), m(2), \dots, m(k)\}$. The coalition $N^{m,m(k)} := \{m(1), m(2), \dots, m(k-1)\}$ is the preceding coalition for player $m(k)$. Due to superadditivity, the participation of player i in the preceding coalition $N^{m,i}$ monotonically increases the collective payoff. This payoff increase, given by $v(N^{m,i} \cup \{i\}) - v(N^{m,i})$, is the i-th player's contribution in permutation m. Assume that every permutation occurs at the same probability. The i-th player's Shapley value is the expected value of contributions for all m:

$$\phi_i := \frac{\sum_{m \in \mathbf{M}} (v(N^{m,i} \cup \{i\}) - v(N^{m,i}))}{(s+1)!}. \tag{3.6}$$

The buyer monotonically increases the collective payoff from zero to $\lambda Q_{\mathbf{B}\cup S_+}$ by joining a seller coalition S_+ (Table 3.1). For each S_+, there are $|S_+|!\,(s-|S_+|)!$ permutations in which the buyer gains a non-zero contribution $\lambda Q_{\mathbf{B}\cup S_+}$. The buyer's Shapley value is written as

$$\phi_{-1} = \frac{\lambda \sum_{S_+\subseteq \mathbf{S}\setminus\varnothing} |S_+|!\,(s-|S_+|)!\,Q_{\mathbf{B}\cup S_+}}{(s+1)!}. \tag{3.7}$$

Let $S_{(j)} \subseteq \mathbf{S}\setminus\{j\}$ be a seller coalition which does not contain seller j. $S_{(j)}$ may be the empty coalition. The j-th seller gains a non-zero contribution $(Q_{T_{(j)}\cup\{j\}} - Q_{T_{(j)}})$ by joining $T_{(j)} := \mathbf{B}\cup S_{(j)}$. $T_{(j)}$ is the buyer coalition or a normal coalition which does not contain seller j. The j-th seller's Shapley value is

$$\phi_j = \frac{\lambda \sum_{S_{(j)}\subseteq \mathbf{S}\setminus\{j\}} |T_{(j)}|!\,(s-|T_{(j)}|)!\,(Q_{T_{(j)}\cup\{j\}} - Q_{T_{(j)}})}{(s+1)!}. \tag{3.8}$$

The Shapley value satisfies social rationality

$$\sum_{i\in\mathbf{N}} \phi_i = v(\mathbf{N}) = \lambda Q_{\mathbf{N}}. \tag{3.9}$$

The collective payoff of the grand coalition is allocated to the players with no loss. The Shapley value also satisfies individual rationality

$$\phi_i \geq v(\{i\}) = 0 \;\text{ for all }\; i\in\mathbf{N}. \tag{3.10}$$

Every player receives a non-negative payoff from the grand coalition.

3.2.4 Permit Price

The buyer receives the Shapley value ϕ_{-1} from the grand coalition $\mathbf{N}$. From $U_{-1}(\mathbf{N}) = \phi_{-1}$, we obtain permit price

$$P = \lambda(1-\pi_{\mathbf{B}}) = \lambda\pi_{\mathbf{S}}, \tag{3.11}$$

where

$$\pi_{\mathbf{B}} := \frac{\phi_{-1}}{v(\mathbf{N})} \;\text{ and }\; \pi_{\mathbf{S}} := \frac{\sum_{j\in\mathbf{S}}\phi_j}{v(\mathbf{N})}. \tag{3.12}$$

$\pi_{\mathbf{B}} \in [0,1]$ and $\pi_{\mathbf{S}} \in [0,1]$ are demand-side and supply-side bargaining power (DBP and SBP), respectively. The DBP is the proportion of the buyer's Shapley value to the collective payoff. Due to the social rationality (Eq. (3.9)), we have $\pi_{\mathbf{B}} + \pi_{\mathbf{S}} = 1$. λ in $v(\mathbf{N})$ is canceled by λ in ϕ_{-1}. Hence the DBP and SBP are independent of the buyer's WTP.

Proposition 2 *Permit price, which satisfies both individual and social rationality, is given by the product of the buyer's WTP and the SBP. The sum of the DBP and SBP is 1.*

3.2.5 Range of Permit Price

Here I demonstrate that permit price ranges from $\lambda/(s+1)$ to $\lambda/2$. The DBP is written as

$$\pi_{\mathbf{B}} = \frac{\sum_{S_+} \#_{S_+}\rho_{S_+}}{(s+1)!}. \tag{3.13}$$

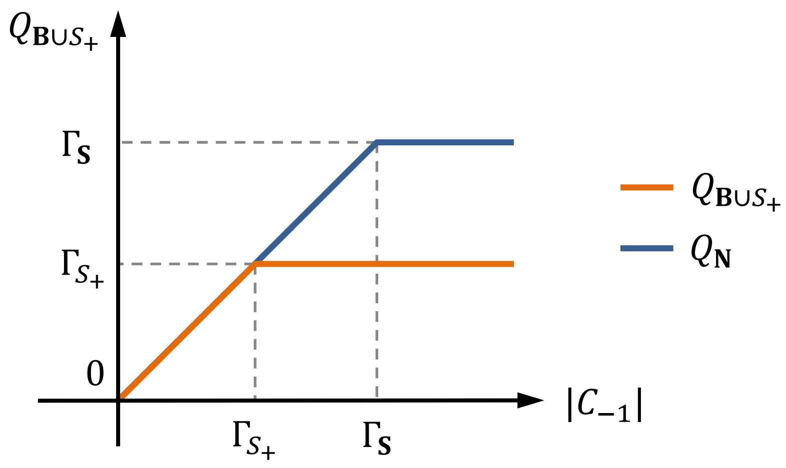

Figure 3.3: Trading volume of permits in a normal coalition $\mathbf{B} \cup S_+$. If permit supply from a seller coalition S_+ (denoted by Γ_{S_+}) is constant, the trading volume $Q_{\mathbf{B}\cup S_+}$ is a piecewise linear and monotonically increasing function of permit demand $|C_{-1}|$.

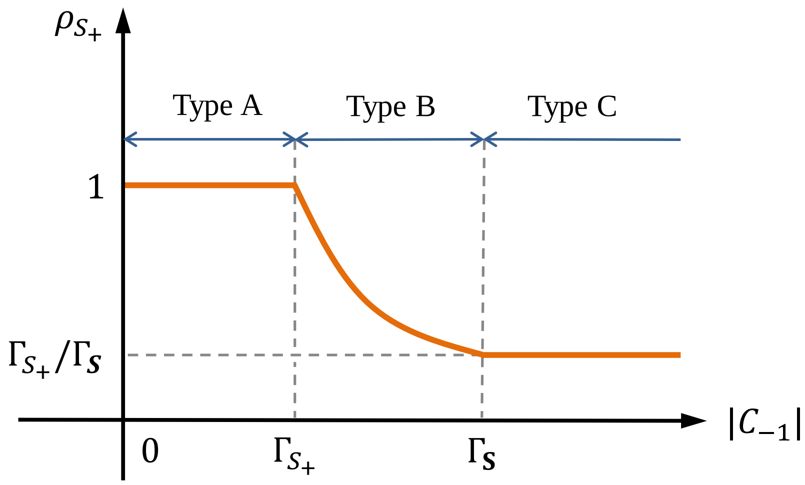

Figure 3.4: Trading volume ratio (TVR) in a normal coalition $\mathbf{B} \cup S_+$. If permit supply Γ_{S_+} is constant, the TVR (denoted by ρ_{S_+}) is a monotonically decreasing function of permit demand $|C_{-1}|$. Depending on the balance between supply and demand, the TVR is classified into three types: (A) $|C_{-1}|/|C_{-1}|$, (B) $\Gamma_{S_+}/|C_{-1}|$, and (C) $\Gamma_{S_+}/\Gamma_{\mathbf{S}}$.

$\#_{S_+} := |S_+|!\,(s - |S_+|)!$ is the number of player permutations in which a seller coalition S_+ precedes the buyer. ρ_{S_+} is trading volume ratio (TVR) defined as

$$\rho_{S_+} := \frac{Q_{\mathbf{B}\cup S_+}}{Q_{\mathbf{N}}} = \frac{\min\{|C_{-1}|, \Gamma_{S_+}\}}{\min\{|C_{-1}|, \Gamma_{\mathbf{S}}\}}. \tag{3.14}$$

The TVR is the proportion of the trading volume in a normal coalition $\mathbf{B} \cup S_+$ to that in the grand coalition $\mathbf{N}$.

If permit supply Γ_{S_+} is constant, the trading volume $Q_{\mathbf{B}\cup S_+}$ is a piecewise monotonically increasing function of permit demand $|C_{-1}|$ (Figure 3.3). Since $\Gamma_{S_+} \leq \Gamma_{\mathbf{S}}$ for all S_+, the TVR is a monotonically decreasing function of $|C_{-1}|$ (Figure 3.4). Depending on the balance between supply and demand, the TVR is classified into three types: (A) $|C_{-1}|/|C_{-1}|$, (B) $\Gamma_{S_+}/|C_{-1}|$, and (C) $\Gamma_{S_+}/\Gamma_{\mathbf{S}}$. The TVR is type A if the supply from S_+ exceeds the demand, i.e., if $|C_{-1}| \leq \Gamma_{S_+}$. The type A has the maximum value of 1. The

TVR is type B if $\Gamma_{S_+} \le |C_{-1}| \le \Gamma_{\mathbf{S}}$. The type B has a value between $\Gamma_{S_+}/\Gamma_{\mathbf{S}}$ and 1. The TVR is type C if the demand exceeds the aggregate supply, i.e., if $\Gamma_{\mathbf{S}} \le |C_{-1}|$. The type C has the minimum value of $\Gamma_{S_+}/\Gamma_{\mathbf{S}}$.

Lower Limit of Permit Price. Suppose that the buyer's WTP is constant. By Eq. (3.11), permit price is minimized by maximizing the DBP. By Eq. (3.13), the DBP is maximized if the TVR is type A for all S_+. This condition is satisfied when permit supply is excessive, i.e., when $|C_{-1}| \le C_j$ for all seller j. Substituting $\rho_{S_+} = 1$ into Eq. (3.13) gives the maximum DBP

$$\pi_{\mathbf{B}}^{\max} = \frac{\sum_{S_+} \#_{S_+}}{(s+1)!}. \tag{3.15}$$

In a player permutation, the buyer is just a border between the preceding coalition S_+ and other sellers $\mathbf{S} \setminus S_+$. $\#_{S_+}$ is equal to the number of seller permutations in which S_+ precedes $\mathbf{S} \setminus S_+$. There are $s!$ seller permutations of s sellers. Each seller permutation $(j(1), j(2), \ldots, j(s))$ is generated from s preceding coalitions (S_+'s):

$$\{j(1)\}, \{j(1), j(2)\}, \ldots, \{j(1), j(2), \ldots, j(s)\}. \tag{3.16}$$

$\sum_{S_+} \#_{S_+}$ counts every seller permutation s times. Hence $\sum_{S_+} \#_{S_+} = s \times s!$. The maximum DBP is

$$\pi_{\mathbf{B}}^{\max} = \frac{s \times s!}{(s+1)!} = \frac{s}{s+1}. \tag{3.17}$$

The lower limit of permit price is

$$P^{\min} = \lambda(1 - \pi_{\mathbf{B}}^{\max}) = \frac{\lambda}{s+1}. \tag{3.18}$$

Upper Limit of Permit Price. Permit price is maximized by minimizing the DBP. The DBP is minimized if the TVR is type C for all S_+. This condition is satisfied when permit demand is excessive, i.e., when $\Gamma_{\mathbf{S}} \le |C_{-1}|$. Substituting $\rho_{S_+} = \Gamma_{S_+}/\Gamma_{\mathbf{S}}$ into Eq. (3.13) gives the minimum DBP

$$\pi_{\mathbf{B}}^{\min} = \frac{\sum_{S_+} \#_{S_+} \Gamma_{S_+}}{(s+1)!\,\Gamma_{\mathbf{S}}} = \frac{\sum_{S_+} (\#_{S_+} \sum_{j \in S_+} C_j)}{(s+1)!\,\Gamma_{\mathbf{S}}}. \tag{3.19}$$

If S_+ contains seller j, $\#_{S_+} C_j$ is added to the numerator of $\pi_{\mathbf{B}}^{\min}$. Let $\mathcal{S}_j$ be the set of seller coalitions containing seller j. Then

$$\pi_{\mathbf{B}}^{\min} = \frac{\sum_{j \in \mathbf{S}} \alpha_j C_j}{(s+1)!\,\Gamma_{\mathbf{S}}}, \tag{3.20}$$

where $\alpha_j := \sum_{S_+ \in \mathcal{S}_j} \#_{S_+}$. Since all sellers have the same ability to form coalitions, α_j should be same for all seller j. We have

$$\pi_{\mathbf{B}}^{\min} = \frac{\alpha_j \Gamma_{\mathbf{S}}}{(s+1)!\,\Gamma_{\mathbf{S}}} = \frac{\alpha_j}{(s+1)!}. \tag{3.21}$$

α_j is calculated as follows. A player permutation is written as Eq. (3.5). If S_+ is the single coalition $\{j\}$, seller j is $m(1)$, the buyer is $m(2)$, and $(s-1)$ sellers follow the buyer. The number of permutations is $(s-1)!$. If S_+ is a two-seller coalition containing seller j, seller j chooses $m(1)$ or $m(2)$, and another seller contained by S_+ takes the remaining position. The buyer is $m(3)$, and $(s-2)$ sellers follow the buyer. The number of permutations is

Table 3.2: **Derivative of the TVR with respect to $|C_{-1}|$**

Type	TVR	Condition	Derivative
A	$\lvert C_{-1}\rvert/\lvert C_{-1}\rvert$	$\lvert C_{-1}\rvert \in (0, \Gamma_{S_+})$	0
B	$\Gamma_{S_+}/\lvert C_{-1}\rvert$	$\lvert C_{-1}\rvert \in (\Gamma_{S_+}, \Gamma_{\mathbf{S}})$	< 0
C	$\Gamma_{S_+}/\Gamma_{\mathbf{S}}$	$\lvert C_{-1}\rvert \in (\Gamma_{\mathbf{S}}, \infty)$	0

$2(s-1)!$. If S_+ is a k-seller coalition containing seller j, the number of permutations is $k(s-1)!$. α_j is the sum of $k(s-1)!$ for all $k \in \{1, 2, \ldots, s\}$, which is

$$\alpha_j = (1 + 2 + \cdots + s)(s-1)! = \frac{(s+1)!}{2}. \tag{3.22}$$

The minimum DBP is

$$\pi_{\mathbf{B}}^{\min} = \frac{1}{2}. \tag{3.23}$$

The upper limit of permit price is

$$P^{\max} = \lambda(1 - \pi_{\mathbf{B}}^{\min}) = \frac{\lambda}{2}. \tag{3.24}$$

Proposition 3 *Let s be the number of sellers. The DBP ranges from $1/2$ to $s/(s+1)$. The DBP is always greater than or equal to the SBP.*

Proposition 4 *Let λ be the buyer's WTP. Permit price ranges from $\lambda/(s+1)$ to $\lambda/2$. Permit price is minimized when permit supply from every seller is greater than or equal to permit demand, and is maximized when permit demand is greater than or equal to the aggregate permit supply.*

3.2.6 Monotonicity of Permit Price

Assume that permit supply and demand are independent of each other. A change in supply (demand) does not change demand (supply). Moreover, assume that the buyer's WTP is constant. Under these assumptions, permit price satisfies three types of monotonicity: (I) Permit price monotonically increases as permit demand increases. (II) Permit price monotonically decreases as permit supply from a seller increases. (III) Permit price monotonically decreases with the entry of a new seller into the market.

Type I Monotonicity. Differentiating Eq. (3.11) with respect to permit demand $|C_{-1}|$ gives

$$\frac{\partial P}{\partial |C_{-1}|} = (1 - \pi_{\mathbf{B}})\frac{\partial \lambda}{\partial |C_{-1}|} - \lambda \frac{\partial \pi_{\mathbf{B}}}{\partial |C_{-1}|}. \tag{3.25}$$

Since $\partial\lambda/\partial|C_{-1}| = 0$, the type I monotonicity holds if $\partial\pi_{\mathbf{B}}/\partial|C_{-1}| \leq 0$.

The TVR (ρ_{S_+}) is continuous over $|C_{-1}| > 0$, and is differentiable almost everywhere (Figure 3.4). The derivative $\partial\rho_{S_+}/\partial|C_{-1}|$ is non-positive for all types of the TVRs (Table 3.2). From Eq. (3.13),

$$\frac{\partial \pi_{\mathbf{B}}}{\partial |C_{-1}|} = \frac{1}{(s+1)!}\sum_{S_+} \#_{S_+} \frac{\partial \rho_{S_+}}{\partial |C_{-1}|} \leq 0. \tag{3.26}$$

Thus permit price satisfies the type I monotonicity.

Table 3.3: Derivative of the TVR with respect to C_j ($j \in S_+$)

Type	TVR	Condition	Derivative
A	$\lvert C_{-1}\rvert/\lvert C_{-1}\rvert$	$\lvert C_{-1}\rvert \in (0, \Gamma_{S_+})$	0
B	$(C_j + \Gamma_{S_+\setminus\{j\}})/\lvert C_{-1}\rvert$	$\lvert C_{-1}\rvert \in (\Gamma_{S_+}, \Gamma_{\mathbf{S}})$	> 0
C	$(C_j + \Gamma_{S_+\setminus\{j\}})/(C_j + \Gamma_{\mathbf{S}\setminus\{j\}})$	$\lvert C_{-1}\rvert \in (\Gamma_{\mathbf{S}}, \infty)$	≥ 0

Table 3.4: Derivative of the TVR with respect to C_j ($j \notin S_+$)

Type	TVR	Condition	Derivative
A	$\lvert C_{-1}\rvert/\lvert C_{-1}\rvert$	$\lvert C_{-1}\rvert \in (0, \Gamma_{S_+})$	0
B	$\Gamma_{S_+}/\lvert C_{-1}\rvert$	$\lvert C_{-1}\rvert \in (\Gamma_{S_+}, \Gamma_{\mathbf{S}})$	0
C	$\Gamma_{S_+}/(C_j + \Gamma_{\mathbf{S}\setminus\{j\}})$	$\lvert C_{-1}\rvert \in (\Gamma_{\mathbf{S}}, \infty)$	< 0

Proposition 5. *Assume that permit supply and demand are independent of each other. If the buyer's WTP is constant, permit price monotonically increases as permit demand increases.*

Type II Monotonicity. Differentiating Eq. (3.11) with respect to permit supply C_j gives

$$\frac{\partial P}{\partial C_j} = (1 - \pi_{\mathbf{B}})\frac{\partial \lambda}{\partial C_j} - \lambda \frac{\partial \pi_{\mathbf{B}}}{\partial C_j}. \tag{3.27}$$

Since $\partial\lambda/\partial C_j = 0$, the type II monotonicity holds if $\partial \pi_{\mathbf{B}}/\partial C_j \geq 0$.

If S_+ contains seller j, the TVR is

$$\rho_{S_+} = \frac{\min\{\lvert C_{-1}\rvert, C_j + \Gamma_{S_+\setminus\{j\}}\}}{\min\{\lvert C_{-1}\rvert, C_j + \Gamma_{\mathbf{S}\setminus\{j\}}\}}. \tag{3.28}$$

The numerator and denominator are piecewise linear and monotonically increasing functions of C_j. The TVR is continuous over $C_j > 0$, and is differentiable almost everywhere. The derivative $\partial \rho_{S_+}/\partial C_j$ is non-negative for all types of the TVRs (Table 3.3). If S_+ does not contain seller j, the TVR is

$$\rho_{S_+} = \frac{\min\{\lvert C_{-1}\rvert, \Gamma_{S_+}\}}{\min\{\lvert C_{-1}\rvert, C_j + \Gamma_{\mathbf{S}\setminus\{j\}}\}}, \tag{3.29}$$

where Γ_{S_+} is independent of C_j. The numerator is constant, and the denominator is same as Eq. (3.28). The derivative $\partial \rho_{S_+}/\partial C_j$ is zero for the types A and B, but is negative for the type C (Table 3.4).

If the TVR is type A or B for all S_+, we obtain $\partial \pi_{\mathbf{B}}/\partial C_j \geq 0$ from Eq. (3.13). If $\lvert C_{-1}\rvert \geq \Gamma_{\mathbf{S}}$, the TVR is type C for all S_+, and the DBP has the minimum value of 1/2 (Proposition 3). Hence $\partial \pi_{\mathbf{B}}/\partial C_j = 0$ if there exists S_+ such that the TVR is type C. Thus, the derivative $\partial \pi_{\mathbf{B}}/\partial C_j$ is non-negative for all S_+, and permit price satisfies the type II monotonicity.

Proposition 6 *Assume that permit supply and demand are independent of each other. If the buyer's WTP is constant, permit price monotonically decreases as permit supply from a seller increases.*

Type III Monotonicity. First, we expand the seller set $\mathbf{S}$ to $\mathbf{Z} := \mathbf{S} \cup \{\sigma\}$ by adding a new seller σ with zero permit supply ($\Gamma_{\{\sigma\}} = 0$). The buyer forms the grand coalition with $\mathbf{Z}$. Similar to Eq. (3.13), the DBP is

$$\pi^\star_{\mathbf{B}} = \frac{\sum_{Z_+ \subseteq \mathbf{Z} \setminus \varnothing} \#^\star_{Z_+} \rho^\star_{Z_+}}{(s+2)!}. \tag{3.30}$$

Z_+ is a non-empty seller coalition. $\#^\star_{Z_+} := |Z_+|!\,(s+1-|Z_+|)!$ is the number of player permutations in which Z_+ precedes the buyer. $\rho^\star_{Z_+} := Q_{\mathbf{B}\cup Z_+}/Q_{\mathbf{B}\cup\mathbf{Z}}$ is the TVR. Eq. (3.11) gives permit price $P^\star = \lambda(1-\pi^\star_{\mathbf{B}})$.

If $Z_+ = \{\sigma\}$, $Q_{\mathbf{B}\cup Z_+} = \min\{|C_{-1}|, \Gamma_{Z_+}\} = 0$ and $\rho^\star_{Z_+} = 0$. Hence $\#^\star_{\{\sigma\}}\rho^\star_{\{\sigma\}} = 0$. If $Z_+ \neq \{\sigma\}$, Z_+ is S_+ or $S_+ \cup \{\sigma\}$. For every S_+, $Q_{\mathbf{B}\cup S_+} = Q_{\mathbf{B}\cup S_+\cup\{\sigma\}}$ and $\rho_{S_+} = \rho^\star_{S_+} = \rho^\star_{S_+\cup\{\sigma\}}$. Moreover,

$$\begin{aligned}
\#^\star_{S_+} + \#^\star_{S_+\cup\{\sigma\}} &= |S_+|!\,(s+1-|S_+|)! + (|S_+|+1)!\,(s-|S_+|)! \\
&= (s+2)|S_+|!\,(s-|S_+|)! \\
&= (s+2)\#_{S_+}.
\end{aligned} \tag{3.31}$$

From Eq. (3.30),

$$\begin{aligned}
\pi^\star_{\mathbf{B}} &= \frac{\#^\star_{\{\sigma\}}\rho^\star_{\{\sigma\}} + \sum_{S_+}(\#^\star_{S_+}\rho^\star_{S_+} + \#^\star_{S_+\cup\{\sigma\}}\rho^\star_{S_+\cup\{\sigma\}})}{(s+2)!} \\
&= \frac{\sum_{S_+}(s+2)\#_{S_+}\rho_{S_+}}{(s+2)!} \\
&= \pi_{\mathbf{B}},
\end{aligned} \tag{3.32}$$

and we obtain $P^\star = P$. The entry of seller σ into the market has no influence on permit price.

Second, we increase permit supply from seller σ to an arbitrary level. By Proposition 6, this operation monotonically decreases permit price. Now we find that permit price satisfies the type III monotonicity.

Proposition 7 *Assume that permit supply and demand are independent of each other. If the buyer's WTP is constant, permit price monotonically decreases with the entry of a new seller into the market.*

3.3 Results and Discussion

The seven propositions derived from the CET game help us understand why buyers could have dominant power in the international permit market. In this section, I summarize the results of the CET game, and calculate the demand-side bargaining power using market data. Finally, I conclude this chapter by discussing limitations and extensions of the CET game.

3.3.1 Withdrawal of Permit Buyers from the Market

In the CET game, a buyer purchases permits from sellers only if the buyer forms a coalition with the sellers. The stability of the coalition depends on the buyer's WTP. The WTP represents the value of the coalition for the buyer. A buyer with a zero WTP withdraws from the market without purchasing permits. Only if there exists a buyer with a positive WTP, permit price can be positive (Proposition 1). The permit price, which satisfies both individual and social rationality, is given by the product of the buyer's WTP and the SBP (Proposition 2). If the SBP is constant, a higher WTP leads to a higher price. Permit price is strongly influenced by the buyer's WTP.

The Kyoto Protocol allows buyers to withdraw from the commitments without paying costs. The international permit market under CP1 has experienced the withdrawal of the top-three buyers: the US, Japan, and Canada (Figure 3.1). The US, which is the largest buyer in Annex B Parties, did not ratify the Kyoto Protocol. In the CET game, the US is a buyer with a zero WTP. Japan has purchased a large amount of permits from transition economies such as Ukraine, Czech, Latvia, and Poland [74], but decided not to participate in the second commitment period (CP2) [47, 48]. After the severe nuclear disaster in Fukushima, Japan abandoned the 2010 Basic Energy Plan in which the promotion of nuclear power generation was emphasized [75]. As of November 2014, all nuclear power plants of Japan are closed for safety reasons, and most of the electricity is supplied from fossil fuel power plants [76]. The increasing dependence on fossil fuels leads to substantial increases in CO_2 emissions [77]. The costs for additional permits, which are expected to be huge under CP2, may have decreased Japan's WTP to zero. Canada also withdrew from the Kyoto Protocol to avoid financial burdens associated with the IET [46, 48]. The withdrawal of the top-three buyers suggests that the buyer's WTP is sensitive to changes in political and economic conditions.

The right of withdrawal can be a threat to sellers in bargaining. Unless a buyer with a positive WTP participates in the coalition, sellers cannot receive benefits from emissions trading. Therefore the buyer's contribution to the coalition (i.e. the buyer's Shapley value) is relatively large. As a result, sellers are forced to suppress permit price to less than $\lambda/2$ (Proposition 4). This result is equivalent to Proposition 3 that the DBP is always greater than or equal to the SBP. Sellers cannot dominate the market even if permit demand is excessive.

3.3.2 Excessive Permit Supply from Transition Economies

The excessive permit supply from transition economies (i.e. hot air) enhances the DBP and decreases permit price. Suppose that permit supply and demand are independent of each other, and that each buyer's WTP is constant. Permit price monotonically decreases as the supply from a seller increases (Proposition 6). A decrease in price means an increase in the DBP (Proposition 2). Figure 3.5 compares the DBP curves in two types of markets: hot and cold markets. Both markets contain 18 sellers ($s = 18$). In the hot market, the supply from each seller is equal to the volume shown in Fig 3.1. In the cold market, the supply from Russia and Ukraine is assumed to be zero. In both markets, the DBP monotonically decreases as the demand increases (Proposition 5). The DBP in the hot market is greater than or equal to the DBP in the cold market. For instance, Japan's DBP is 0.848 in the hot market, and is 0.786 in the cold market. The supply from Russia and Ukraine enables Japan to purchase permits at a 29% discount (Eq. (3.11)). Thus the hot air reinforces the demand-side dominance in the international permit market.

As discussed by many authors [49–54], the absence of the US from the market has accelerated the downward trend in permit price. The DBP of the US is 0.664 in the hot market (Figure 3.5). If the US has the same WTP as Japan, the price for the US is 120% higher than that for Japan (Eq. (3.11)). From this result, we immediately find that the withdrawal of Japan and Canada from the market would decrease permit price. Buyers with smaller demands have higher DBPs, and purchase permits at lower prices.

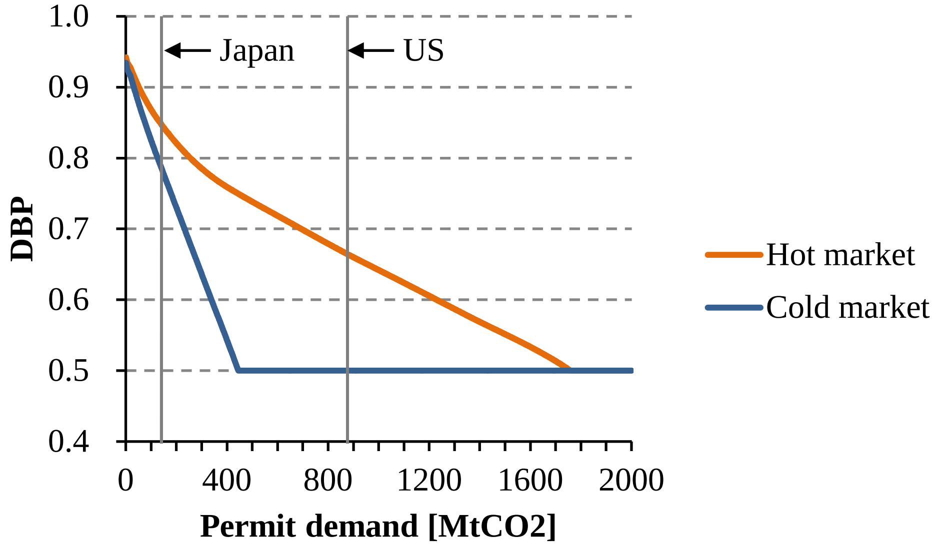

Figure 3.5: Curves of the demand-side bargaining power (DBP) in hot and cold markets. The DBP is obtained by putting the number of sellers (s), supply data ($C_1, C_2, \ldots, C_s$), and demand data ($|C_{-1}|$) in Eq. (3.12). Data set of Figure 3.1 are used for calculation. Both markets contain 18 sellers ($s = 18$; Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Germany, Hungary, Latvia, Lithuania, Monaco, Poland, Romania, Russian Federation, Slovakia, Sweden, Ukraine, and the UK). In the hot market, the supply from each seller is equal to the volume shown in Figure 3.1. In the cold market, the supply from Russia and Ukraine is assumed to be zero. Each curve consists of 2,000 points of the DBPs corresponding to $|C_{-1}| = 1, 2, \ldots, 2000$ ($MtCO_2$).

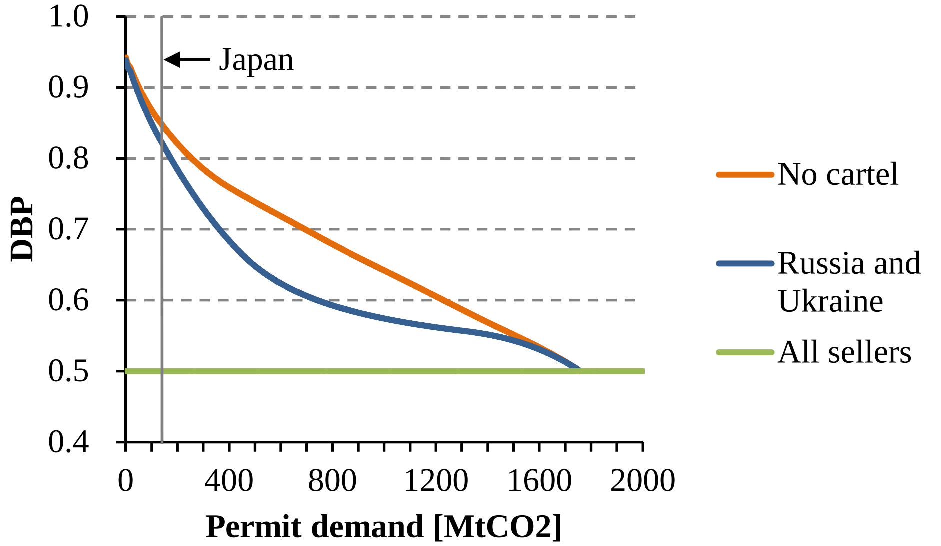

Figure 3.6: Impacts of seller cartels on the DBP. Calculated using the data set of Figure 3.1. The cartel of Russia and Ukraine controls 75% of the aggregate permit supply.

Meanwhile, Russia decided not to participate in CP2 [48]. The withdrawal of Russia from the market means a substantial decrease in the aggregate supply, which may bring upward pressure on permit price (Proposition 7).

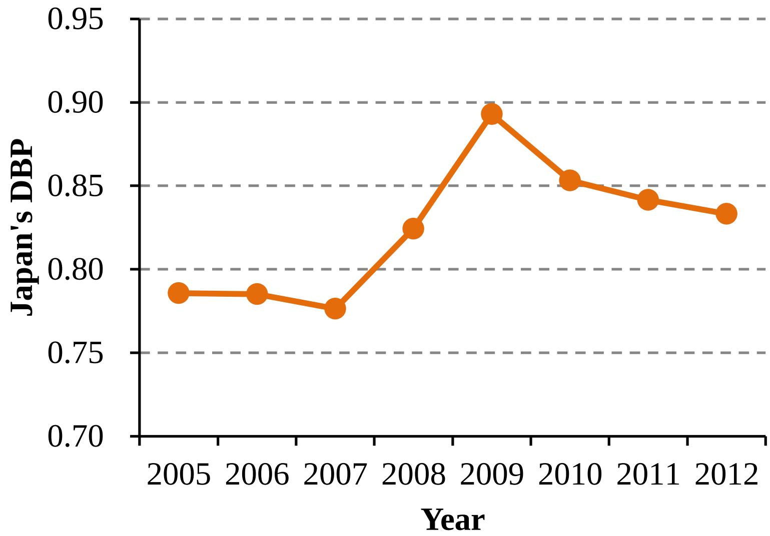

Figure 3.7: Japan's DBP between 2005 and 2012. Permit data were calculated by the author from CO_2 emission data [42] and the QELRC of the Kyoto Protocol [33]. The number of sellers ranged from 12 in 2005 to 21 in 2012.

3.3.3 Market power of seller cartels

Previous studies conclude that transition economies can increase permit price by forming seller cartels [50–52, 54, 57]. However, the demand-side dominance resists market power of seller cartels. Figure 3.6 shows the DBP curves under no cartel, the cartel of Russia and Ukraine, and the cartel of all sellers. The cartel of Russia and Ukraine controls 75% of the aggregate permit supply (Figure 3.1). If sellers form a cartel, the sellers disappear from the market, which decreases the DBP (Proposition 7). At the same time, the seller cartel with a large supply enters the market, which increases the DBP. The cartel of Russia and Ukraine increases the SBP (decreases the DBP). For instance, Japan's DBP decreases from 0.848 (under no cartel) to 0.822, which implies a 17% increase in permit price (Eq. (3.11)). The SBP achieves the maximum value of 0.5 when all sellers form the grand cartel ($s = 1$, Proposition 3). In this case, the SBP is equal to the DBP (Proposition 2). The formation of seller cartels weakens the demand-side dominance, but cannot reverse it.

3.3.4 Impacts of the Global Financial Crisis

The 2008–2009 global financial crisis slowed down economic growth in Annex B Parties. Due to the economic downturn, CO_2 emissions from the Parties except the US decreased from 8,382 $MtCO_2$ in 2008 to 7,803 $MtCO_2$ in 2009 [42]. The Kyoto Protocol has no mechanism to adjust the balance between permit supply and demand. Since the permit allocation to each country was fixed, the decrease in CO_2 emissions increased the supply from transition countries, and decreased the demand of Japan, Canada, and other buyers (Figure 3.2). By Propositions 5 and 6, permit price monotonically decreases as permit supply (demand) increases (decreases). Figure 3.7 shows Japan's DBP between 2005 and 2012. Japan's DBP increased from 0.776 in 2007 to 0.893 in 2009, which implies a 52% decrease in permit price (Eq. (3.11)). Thus the global financial crisis has contributed to the demand-side dominance in the international permit market.

In the real market, AAU price responded to the global financial crisis with a time

Table 3.5: Characteristic function of the multi-buyer CET game ($b = 2$, $s = 1$, $|C_{-1}| = |C_{-2}| = 10$, $C_1 = 10$, $\lambda_{-1} = 1$, $\lambda_{-2} = 2$, $r_{-1} = r_{-2} = 5$). In this case, the participation of buyer -1 into the coalition $\{-2, 1\}$ decreases the collective payoff. The characteristic function v does not satisfy superadditivity.

Coalition N	Collective payoff $v(N)$
ϕ	0
$\{-1\}$	0
$\{-2\}$	0
$\{1\}$	0
$\{-1, -2\}$	0
$\{-1, 1\}$	$\lambda_{-1}Q_{\{-1,1\}} = 10$
$\{-2, 1\}$	$\lambda_{-2}Q_{\{-2,1\}} = 20$
$\{-1, -2, 1\}$	$\lambda_{-1}r_{-1} + \lambda_{-2}r_{-2} = 15$

lag. The annual average price of AAUs peaked in 2009, and plunged in 2011 [36–38]. This time lag is attributed to a time-consuming process of international bargaining. In March 2009, Japan and Ukraine concluded a contract for the transfer of 30 $MtCO_2$ after spending eight months in bargaining [78]. Another contract for the transfer of 40 $MtCO_2$ from Czech to Japan, which was concluded in the same month, required six months of bargaining [79]. The AAU prices specified in these contracts reflect market conditions before the recession.

3.3.5 Future Research

A merit of the CET game is that we can calculate each country's bargaining power in the international permit market. However, the CET game uses three assumptions to simplify the calculation. First, the players form the grand coalition. Although this assumption is popular in cooperative games, there is no strong evidence. In the real world, countries need to pay costs for international bargaining. A large coalition containing many players may not be efficient. Moreover, there may exist a pair of countries which cannot cooperate with each other for political reasons. In general, each buyer's WTP varies according to sellers. These factors affect the characteristic function of the CET game. If the characteristic function loses superadditivity, a sub-coalition containing a limited number of countries would be formed. Results from non-cooperative games suggest that the grand coalition is unstable in international climate negotiations [59–61, 63]. A direction of future research is to couple the CET game with non-cooperative games which describe the formation of stable coalitions.

Second, the CET game excludes coalitions containing more than one buyer (multi-buyer coalitions). The multi-buyer CET game is a natural extension of the CET game, but this extension makes the determination of the payoff allocation difficult. Let $\mathbf{B} = \{-1, -2, \ldots, -b\}$ be the buyer set, and let $\mathbf{S} = \{1, 2, \ldots, s\}$ be the seller set. Buyer $i \in \mathbf{B}$ has a demand of $|C_i|$ ($C_i < 0$), and seller $j \in \mathbf{S}$ has a supply of C_j ($C_j > 0$). Let λ_i be each buyer's WTP. In the grand coalition $\mathbf{N} = \mathbf{B} \cup \mathbf{S}$, trading volume of permits is given by $Q_{\mathbf{N}} = \min\{\sum_{i \in \mathbf{B}} |C_i|, \sum_{j \in \mathbf{S}} C_j\}$. Clearly, the total payoff of all sellers is $PQ_{\mathbf{N}}$. Let $r_i \in [0, |C_i|]$ be the volume of permits transferred from sellers to buyer i ($\sum_i r_i = Q_{\mathbf{N}}$). Each buyer's payoff function is $(\lambda_i - P)r_i$, and the total payoff of all buyers is $\sum_i \lambda_i r_i - PQ_{\mathbf{N}}$. The collective payoff of the grand coalition is $\sum_i \lambda_i r_i$. The characteristic function of this game may not satisfy superadditivity (Table 3.5). In this example, we cannot expect the formation of the grand coalition. Even if the grand coalition is formed, the Shapley value does not satisfy individual rationality. This observation suggests that multi-buyer coalitions are generally unstable. A different approach is required to solve the multi-buyer CET game.

Third, the CET game determines the payoff allocation by Shapley value. Shapley value is a popular solution concept for coalitional games, but various alternatives have been proposed [67]. The choice of a solution concept may affect the results of the CET game. Gately [73] proposed the payoff allocation based on propensity to disrupt. In the CET game, the i-th player's propensity to disrupt ($i \in \mathbf{N}$) is given by

$$d_i := \frac{\sum_{j \in \mathbf{N} \setminus \{i\}} U_j - v(\mathbf{N} \setminus \{i\})}{U_i - v(\{i\})} = \frac{v(\mathbf{N}) - v(\mathbf{N} \setminus \{i\})}{U_i} - 1, \tag{3.33}$$

where U_i denotes the i-th player's payoff in the grand coalition. A high propensity to disrupt means that the participation of player i in the grand coalition is highly beneficial to the other players but is not to the player. Gately's solution is the payoff allocation $\{\phi'_i \mid i \in \mathbf{N}\}$ such that $d_i = d_j$ for all $j \in \mathbf{N} \setminus \{i\}$.

Here I compare the DBP based on Shapley value (Shapley-DBP) with the DBP based on propensity to disrupt (Gately-DBP). In the three-player CET game with the grand coalition $\mathbf{N} = \{-1, 1, 2\}$,

$$\phi'_{-1} = \frac{\lambda Q_{\mathbf{N}}^2}{3Q_{\mathbf{N}} - Q_{\{-1,1\}} - Q_{\{-1,2\}}}. \tag{3.34}$$

The Shapley-DBP is

$$\pi_{\mathbf{B}}^{\mathrm{S}} := \frac{\phi_{-1}}{v(\mathbf{N})} = \frac{2Q_{\mathbf{N}} + Q_{\{-1,1\}} + Q_{\{-1,2\}}}{6Q_{\mathbf{N}}}, \tag{3.35}$$

and the Gately-DBP is

$$\pi_{\mathbf{B}}^{\mathrm{G}} := \frac{\phi'_{-1}}{v(\mathbf{N})} = \frac{Q_{\mathbf{N}}}{3Q_{\mathbf{N}} - Q_{\{-1,1\}} - Q_{\{-1,2\}}}. \tag{3.36}$$

The difference between the two DBPs is

$$\pi_{\mathbf{B}}^{\mathrm{G}} - \pi_{\mathbf{B}}^{\mathrm{S}} = \frac{(Q_{\{-1,1\}} + Q_{\{-1,2\}} - Q_{\mathbf{N}})(Q_{\{-1,1\}} + Q_{\{-1,2\}})}{6Q_{\mathbf{N}}(3Q_{\mathbf{N}} - Q_{\{-1,1\}} - Q_{\{-1,2\}})} \geq 0 \tag{3.37}$$

because $Q_{\{-1,1\}} + Q_{\{-1,2\}} \geq Q_{\mathbf{N}}$. The Gately-DBP is greater than or equal to the Shapley-DBP. This result indicates that Gately's solution also supports the demand-side dominance in the international permit market. If permit supply is excessive, i.e., if $|C_{-1}| \leq C_1$ and $|C_{-1}| \leq C_2$, we obtain

$$\pi_{\mathbf{B}}^{\mathrm{S}} = \frac{2}{3} \text{ and } \pi_{\mathbf{B}}^{\mathrm{G}} = 1. \tag{3.38}$$

Gately's solution gives the extreme payoff allocation in which the buyer monopolizes the collective payoff. From $U_{-1} = \phi'_{-1}$ (Eq. (3.1)), permit price is zero. If permit demand is excessive, i.e., if $|C_{-1}| \geq C_1$ and $|C_{-1}| \geq C_2$, we obtain

$$\pi_{\mathbf{B}}^{\mathrm{S}} = \pi_{\mathbf{B}}^{\mathrm{G}} = \frac{1}{2}. \tag{3.39}$$

In this case, the Gately-DBP is equal to the Shapley-DBP.

3.4 Summary and Conclusion

Rapid reduction of anthropogenic greenhouse gas emissions is required to mitigate disastrous impacts of climate change. The Kyoto Protocol introduced international emissions trading (IET) to accelerate the reduction of carbon dioxide (CO_2) emissions. The IET controls CO_2 emissions through the allocation of marketable emission permits to countries. High permit prices provide industrialized countries with an incentive to reduce their CO_2 emissions. However, the IET under the first commitment period (CP1) has suffered from low prices. The downward trend in permit price is attributed to the deficiencies of the Kyoto Protocol: weak compliance enforcement, the generous allocation of permits to transition economies (known as hot air), and the withdrawal of the US. Market data suggest that the international permit market under CP1 was a buyer's market dominated by price-making buyers. In this chapter, I develop a coalitional game of the IET, and demonstrate that permit buyers have dominant bargaining power under the Kyoto Protocol. In my model, called cooperative emissions trading (CET) game, a buyer purchases permits from sellers only if the buyer forms a coalition with the sellers. Permit price is determined by bargaining among the members of a coalition. Using Shapley value, I evaluated the demand-side and supply-side bargaining power (DBP and SBP) in the market. The main results are as follows: (1) Permit price is given by the product of the buyer's willingness-to-pay and the SBP ($= 1 - $DBP). (2) The DBP is greater than or equal to the SBP. These results indicate that buyers can suppress permit price to a low level through bargaining. The deficiencies of the Kyoto Protocol enhance the DBP, and contribute to the demand-side dominance in the international permit market.

Table 4.1: Payoff matrix of the energy choice game coupled with the CET game.

	C	D
C	$-E_1P_\mathrm{C}$, $-E_2P_\mathrm{C}$	$-E_1P_\mathrm{C}+\frac{1}{2}\lambda_1Q_1$, $-E_2P_\mathrm{D}+\frac{1}{2}\lambda_1Q_1$
D	$-E_1P_\mathrm{D}+\frac{1}{2}\lambda_2Q_2$, $-E_2P_\mathrm{C}+\frac{1}{2}\lambda_2Q_2$	$-E_1P_\mathrm{D}$, $-E_2P_\mathrm{D}$

Chapter 4

Discussion

The mosquito net game and the CET game were static games with complete information. I conclude this doctoral thesis by discussing the extension of the two games into dynamic games with incomplete information.

4.1 Energy Choice under Emissions Trading

Consider a two-player non-cooperative game as follows. The set of players is $\mathbf{N} := \{1, 2\}$. Each player $i \in \mathbf{N}$ uses E_i of energy for economic activities. Two types of energy are available: $\Sigma := \{\mathrm{C}, \mathrm{D}\}$. Energy C has a positive CO_2 intensity (CO_2 emissions per unit of energy use), while energy D has a zero CO_2 intensity. Energy C is cheaper than energy D. Each player chooses energy C or D. Let $\sigma_i \in \Sigma$ be the energy type chosen by player i. Let I_{σ_i} and P_{σ_i} be CO_2 intensity and price of energy σ_i, respectively. Then $I_\mathrm{C} > I_\mathrm{D} = 0$ and $P_\mathrm{C} < P_\mathrm{D}$. Each player's energy cost is given by $-E_iP_{\sigma_i}$. Clearly, the use of energy C is the dominant strategy for both players. This energy choice game has the dominant strategy equilibrium (C, C). The total CO_2 emissions are $(E_1 + E_2)I_\mathrm{C}$.

The result of the energy choice game is pessimistic. Here I couple the energy choice game with the CET game to improve the solution. The players play the CET game after the energy choice game. Assume that each player has permits of $E_i\bar{I}$ ($\bar{I} \in (0, I_\mathrm{C})$) in advance. A player using energy C is a permit buyer, and a player using energy D is a permit seller. If both players choose the same type of energy, no permit transfer occurs. Table 4.1 is the payoff matrix of the coupled game. λ_i denotes the WTP of player i, and Q_i denotes the volume of permits transferred from player i to another player. The Nash equilibrium of this payoff matrix is illustrated as Figure 4.1. In the coupled game, the use of energy D can be an individually rational strategy. If $\lambda_1 \geq L_{21} := 2E_2(P_\mathrm{D} - P_\mathrm{C})/Q_1$ or $\lambda_2 \geq L_{12} := 2E_1(P_\mathrm{D} - P_\mathrm{C})/Q_2$, a player chooses energy D, and sells surplus permits to

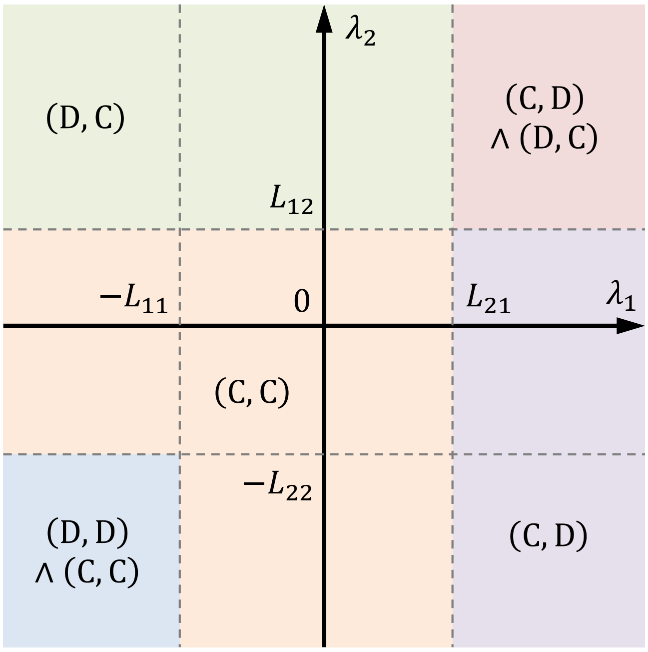

Figure 4.1: Distribution of Nash equilibria of the energy choice game coupled with the CET game. The border L_{ij} $(i, j \in \mathbf{N})$ is given by $2E_i(P_\mathrm{D} - P_\mathrm{C})/Q_j$. In the coupled game, the use of energy D can be an individually rational strategy. However, the Nash equilibrium of (D, D) is achieved only if the players are subsidized ($\lambda_1 < 0$ and $\lambda_2 < 0$).

another player. The total CO_2 emissions decrease from $(E_1 + E_2)P_\mathrm{C}$ to E_1P_C or E_2P_C. This result suggests that emissions trading contributes to the shift from energy C to D. However, the Nash equilibrium of (D, D) is achieved only if the players are subsidized ($\lambda_1 < 0$ and $\lambda_2 < 0$). In the CET game, both buyers and sellers receive benefits from emissions trading. Therefore the players attracted to (C, D) or (D, C) cannot move to (D, D).

The above game assumes complete information. Every player has all information relevant to its payoff, and can choose the best response to the other player's strategy. In this case, the Nash equilibrium is expected to be achieved. However, it is usually difficult for us to know other people's WTPs in advance. If information about the WTPs is incomplete, a player is forced to choose a strategy under uncertainty. As a result, a solution achieved by players may deviate from the Nash equilibrium. The energy choice game with incomplete information can be solved by reinforcement learning. Each player stochastically chooses a strategy based on its preference. The preference is updated by the payoff allocation at the solution. The updating process is described by the Roth-Erev model [80, 81]. The players approach a mixed strategy equilibrium as the number of iterations increases.

4.2 ITN Use and Minority Game

In the mosquito net game with complete information, the players know the true values of the ITN parameters (α_1, α_2, and β). Obviously, this assumption is not realistic. People living in malaria endemic areas may know that proper ITN use contributes to malaria prevention, and may know that improper ITN use enhances their labor productivity. However, it is difficult to measure the ITN parameters in advance. In the mosquito net game with incomplete information, each player needs to predict other players' strategies based on experience. If most of the players choose strategy T (proper ITN use), the infection probability becomes low, and strategy F (improper ITN use) is profitable. If most of the players choose strategy F, the infection probability remains high, and strategy T is profitable. Although the payoff allocation at a solution depends on the ITN parameters, a minority is expected to win the game. The payoff allocation at each time step is reflected in the players' actions at the next time step. This game has a similar structure to the minority game [82]. The minority game is a mathematical formulation of the El Farol Bar problem proposed by Brian Arthur [83]. A clear review on the minority game is provided by Esteban Moro [84].

Bibliography

[1] Stiglitz JE, Walsh CE (2002) Economics. New York: W.W. Norton & Company, 3rd edition.

[2] Arrow KJ (1951) An extension of the basic theorems of classical welfare economics. In: Proceedings of the Second Berkeley Symposium on Mathematical Statistics and Probability, Berkeley: University of California Press. pp. 507–532.

[3] Debreu G (1954) Valuation equilibrium and pareto optimum. PNAS 40: 588–592.

[4] von Neumann J, Morgenstern O (2004) Theory of Games and Economic Behavior. Princeton: Princeton University Press, sixtieth-anniversary edition.

[5] Nowak MA (2006) Evolutionary Dynamics: Exploring the Equations of Life. Cambridge, Massachusetts, and London: Belknap Press.

[6] Nash JF (1950) Equilibrium points in n-person games. Proceedings of the National Academy of Sciences of the United States of America 36: 48–49.

[7] Nash JF (1951) Non-cooperative games. Annals of Mathematics 54: 286–295.

[8] Dawes RM (1980) Social dilemmas. Annual Review of Psychology 31: 169–193.

[9] Siebert H (2008) Economics of the Environment: Theory and Policy. Berlin, Heidelberg, New York: Springer, 7th edition.

[10] Tietenberg T, Lewis L (2011) Environmental & Natural Resource Economics. Upper Saddle River: Prentice Hall, 9th edition.

[11] Shapley LS (1953) A value for n-person games. In: Kuhn HW, Tucker AW, editors, Contribution to the Theory of Games II, Annals of Mathematics Studies 28, Princeton: Princeton University Press. pp. 307–317.

[12] Peleg B, Sudhölter P (2007) Introduction to the Theory of Cooperative Games. Berlin, Heidelberg, New York: Springer, 2nd edition.

[13] Shapley LS, Shubik M (1954) A method for evaluating the distribution of power in a committee system. American Political Science Association 48: 787–792.

[14] Honjo K, Chaves LF, Satake A, Kaneko A, Minakawa N (2013) When they don't bite, we smell money: understanding malaria bednet misuse. Parasitology 140: 580–586.

[15] Honjo K, Satake A (2014) N-player mosquito net game: Individual and social rationality in the misuse of insecticide-treated nets. Journal of Theoretical Biology 342: 39–46.

[16] World Health Organization (2013) World Malaria Report 2013. World Health Organization, Geneva, Switzerland. URL http://www.who.int/malaria/publications/world_malaria_report_2013/en/.

[17] Sachs J, Malaney P (2002) The economic and social burden of malaria. Nature 415: 680–685.

[18] Fegan GW, Noor AM, Akhwale WS, Cousens S, Snow RW (2007) Effect of expanded insecticide-treated bednet coverage on child survival in rural Kenya: a longitudinal study. Lancet 370: 1035–1039.

[19] Chaves LF, Kaneko A, Taleo G, Pascual M, Wilson ML (2008) Malaria transmission pattern resilience to climatic variability is mediated by insecticide-treated nets. Malaria Journal 7: 100.

[20] Lindblade KA, Eisele TP, Gimnig JE, Alaii JA, Odhiambo F, et al. (2004) Sustainability of reductions in malaria transmission and infant mortality in western Kenya with use of insecticide-treated bednets. The Journal of the American Medical Association 291: 2571–2580.

[21] Minakawa N, Dida GO, Sonye GO, Futami K, Kaneko S (2008) Unforeseen misuses of bed nets in fishing villages along Lake Victoria. Malaria Journal 7: 165.

[22] Baume CA, Reithinger R, Woldehanna S (2009) Factors associated with use and non-use of mosquito nets owned in Oromia and Amhara Regional States, Ethiopia. Malaria Journal 8: 264.

[23] Lover AA, Sutton BA, Asy AJ, Wilder-Smith A (2011) An exploratory study of treated-bed nets in Timor-Leste: patterns of intended and alternative usage. Malaria Journal 10: 199.

[24] Howard SC, Omumbo J, Nevill C, Some ES, Donnelly CA, et al. (2000) Evidence for a mass community effect of insecticide-treated bednets on the incidence of malaria on the Kenyan coast. Transactions of the Royal Society of Tropical Medicine and Hygiene 94: 357–360.

[25] Hawley WA, Phillips-Howard PA, ter Kuile FO, Terlouw DJ, Vulule JM, et al. (2003) Community-wide effects of permethrin-treated bed nets on child mortality and malaria morbidity in western Kenya. The American Journal of Tropical Medicine and Hygiene 68: 121–127.

[26] Killeen GF, Smith TA, Ferguson HM, Mshinda H, Abdulla S, et al. (2007) Preventing childhood malaria in Africa by protecting adults from mosquitoes with insecticide-treated nets. PLOS Medicine 4: e229.

[27] Baumol WJ, Oates WE (1988) The Theory of Environmental Policy. Cambridge: Cambridge University Press, 2nd edition.

[28] Intergovernmental Panel on Climate Change (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, New York: Cambridge University Press. URL http://www.ipcc.ch/report/ar5/wg1/.

[29] Hansen J, Kharecha P, Sato M, Masson-Delmotte V, Ackerman F, et al. (2013) Assessing "dangerous climate change": Required reduction of carbon emissions to protect young people, future generations and nature. PLOS ONE 8: e81648.

[30] Intergovernmental Panel on Climate Change (2014) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, New York: Cambridge University Press. URL http://www.ipcc.ch/report/ar5/wg2/.

[31] Intergovernmental Panel on Climate Change (2014) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, New York: Cambridge University Press. URL http://www.ipcc.ch/report/ar5/wg2/.

[32] Intergovernmental Panel on Climate Change (2014) Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, New York: Cambridge University Press. URL http://www.ipcc.ch/report/ar5/wg3/.

[33] United Nations Framework Convention on Climate Change (1998) Kyoto Protocol to the United Nations Framework Convention on Climate Change. URL https://unfccc.int/kyoto_protocol/items/2830.php.

[34] Oberthür S, Ott HE (1999) The Kyoto Protocol: International Climate Policy for the 21st Century. Berlin, Heidelberg: Springer-Verlag.

[35] Tietenberg T (2006) Emissions Trading: Principles and Practice. Washington, DC: Resources for the Future, 2nd edition.

[36] Kossoy A, Ambrosi P (2010) State and Trends of the Carbon Market 2010. Washington, DC: World Bank. URL http://hdl.handle.net/10986/13401.

[37] Linacre N, Kossoy A, Ambrosi P (2011) State and Trends of the Carbon Market 2011. Washington, DC: World Bank. URL http://hdl.handle.net/10986/13400.

[38] Kossoy A, Guigon P (2012) State and Trends of the Carbon Market 2012. Washington, DC: World Bank. URL http://hdl.handle.net/10986/13336.

[39] Kossoy A, Oppermann K, Reddy RC, Bosi M, Boukerche S, et al. (2013) Mapping Carbon Pricing Initiatives 2013: Developments and Prospects. Washington, DC: World Bank. URL http://hdl.handle.net/10986/15771.

[40] Intergovernmental Panel on Climate Change (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. URL http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html.

[41] Ackerman F, Stanton EA (2012) Climate risks and carbon prices: Revising the social cost of carbon. Economics: The Open-Access, Open-Assessment E-Journal 6: 1–25.

[42] United Nations Framework Convention on Climate Change (2014) Total CO_2 Emissions without Land Use, Land-Use Change and Forestry. URL http://unfccc.int/ghg_data/ghg_data_unfccc/time_series_annex_i/items/3814.php.

[43] Barrett S (2008) Climate treaties and the imperative of enforcement. Oxford Review of Economic Policy 24: 239–258.

[44] Aakre S, Hovi J (2010) Emission trading: Participation enforcement determines the need for compliance enforcement. European Union Politics 11: 427–445.

[45] United Nations Framework Convention on Climate Change (2002) Report of the Conference of the Parties on its seventh session, held at Marrakesh from 29 October to 10 November 2001. Addendum. Part II: Action taken by the Conference of the Parties. Volume III. URL http://unfccc.int/bodies/body/6383/php/view/reports.php.

[46] Curry B, McCarthy S (2011) Canada formally abandons Kyoto Protocol on climate change. The Globe and Mail (published December 12, 2011). URL http://www.theglobeandmail.com/news/politics/canada-formally-abandons-kyoto-protocol-on-climate-change/article4180809/.

[47] The Asahi Shimbun (2011) Japan should not walk away from Kyoto Protocol (published December 13, 2011). URL http://ajw.asahi.com/article/views/editorial/AJ201112130008.

[48] United Nations Framework Convention on Climate Change (2012) Doha Amendment to the Kyoto Protocol. URL http://unfccc.int/kyoto_protocol/doha_amendment/items/7362.php.

[49] Hagem C, Holtsmark B (2001) From small to insignificant: Climate impact of the Kyoto Protocol with and without the US. Policy Note 2001:01. Oslo: CICERO. URL http://www.cicero.uio.no/publications/detail.aspx?id=1315&lang=en.

[50] Böhringer C (2002) Climate politics from kyoto to bonn: From little to nothing? The Energy Journal 23: 427–445.

[51] Springer U (2003) The market for tradable ghg permits under the kyoto protocol: A survey of model studies. Energy Economics 25: 527–551.

[52] Springer U, Varilek M (2004) Estimating the price of tradable permits for greenhouse gas emissions in 2008–12. Energy Policy 32: 611–624.

[53] Nordhaus WD (2001) Global warming economics. Science 294: 1283–1284.

[54] Manne A, Richels R (2004) Us rejection of the kyoto protocol: The impact on compliance costs and co_2 emissions. Energy Policy 32: 447–454.

[55] Montgomery WD (1972) Markets in licenses and efficient pollution control programs. Journal of Economic Theory 5: 395–418.

[56] Hahn RW (1984) Market power and transferable property rights. The Quarterly Journal of Economics 99: 753–765.

[57] Maeda A (2003) The emergence of market power in emission rights markets: The role of initial permit distribution. Journal of Regulatory Economics 24: 293–314.

[58] Godal O, Meland F (2010) Permit markets, seller cartels and the impact of strategic buyers. The BE Journal of Economic Analysis & Policy 10: Article 29.

[59] Carraro C, Siniscalco D (1993) Strategies for the international protection of the environment. Journal of Public Economics 52: 309–328.

[60] Barrett S (1994) Self-enforcing international environmental agreements. Oxford Economic Papers 46: 878–894.

[61] Carraro C, Siniscalco D (1998) International environmental agreements: Incentives and political economy. European Economic Review 42: 561–572.

[62] Dutta PK, Radner R (2004) Self-enforcing climate-change treaties. PNAS 101: 5174–5179.

[63] Asheim GB, Froyn CB, Hovi J, Menz FC (2006) Regional versus global cooperation for climate control. Journal of Environmental Economics and Management 51: 93–109.

[64] Pittel K, Rübbelke DTG (2008) Climate policy and ancillary benefits: A survey and integration into the modelling of international negotiations on climate change. Ecological Economics 68: 210–220.

[65] DeCanio SJ, Fremstad A (2013) Game theory and climate diplomacy. Ecological Economics 85: 177–187.

[66] Madani K (2013) Modeling international climate change negotiations more responsibility: Can highly simplified game theory models provide reliable policy insights? Ecological Economics 90: 68–76.

[67] Parrachino I, Zara S, Patrone F (2006) Cooperative game theory and its application to natural, environmental and water resource issues: 1. basic theory. World Bank Policy Research Working Paper 4072. Washington, DC: World Bank. URL http://dx.doi.org/10.1596/1813-9450-4072.

[68] Parrachino I, Dinar A, Patrone F (2006) Cooperative game theory and its application to natural, environmental, and water resource issues: 3. application to water resources. World Bank Policy Research Working Paper 4074. Washington, DC: World Bank. URL http://dx.doi.org/10.1596/1813-9450-4074.

[69] Zara S, Dinar A, Patrone F (2006) Cooperative game theory and its application to natural, environmental, and water resource issues: 2. application to natural and environmental resources. World Bank Policy Research Working Paper 4073. Washington, DC: World Bank. URL http://dx.doi.org/10.1596/1813-9450-4073.

[70] Madani K (2010) Game theory and water resources. Journal of Hydrology 381: 225–238.

[71] Bailey M, Sumaila UR, Lindroos M (2010) Application of game theory to fisheries over three decades. Fisheries Research 102: 1–8.

[72] Finus M, Rübbelke DTG (2013) Public good provision and ancillary benefits: The case of climate agreements. Environmental and Resource Economics 56: 211–226.

[73] Gately D (1974) Sharing the gains from regional cooperation: A game theoretic application to planning investment in electric power. International Economic Review 15: 195–208.

[74] New Energy and Industrial Technology Development Organization, Japan (2012) Kyoto mechanisms. URL http://www.nedo.go.jp/english/introducing_project1_10.html.

[75] Duffield JS, Woodall B (2011) Japan's new basic energy plan. Energy Policy 39: 3741–3749.

[76] Federation of Electric Power Companies of Japan (2014) Electricity Generated and Purchased in November 2014 (Bulletin). URL http://www.fepc.or.jp/english/news/generated_purchased/index.html.

[77] Honjo K, Fujii M (2014) Impacts of demographic, meteorological, and economic changes on household CO_2 emissions in the 47 prefectures of Japan. Regional Science Policy & Practice 6: 13–30.

[78] New Energy and Industrial Technology Development Organization, Japan (2009) News release (19 March, 2009). URL http://www.nedo.go.jp/news/press/AA5_0063A.html.

[79] New Energy and Industrial Technology Development Organization, Japan (2009) News release (31 March, 2009). URL http://www.nedo.go.jp/news/press/AA5_0075A.html.

[80] Roth AE, Erev I (1995) Learning in extensive-form games: Experimental data and simple dynamic models in the intermediate term. Games and Economic Behavior 8: 164–212.

[81] Erev I, Roth AE (1998) Predicting how people play games: Reinforcement learning in experimental game with unique, mixed strategy equilibria. The American Economic Review 88: 848–881.

[82] Challet D, Zhang Y-C (1997) Emergence of cooperation and organization in an evolutionary game. Physica A 246: 407–418.

[83] Arthur WB (1994) Inductive reasoning and bounded rationality. The American Economic Review 84: 406–411.

[84] Moro E (2004) The minority game: An introductory guide. In: Korutcheva E, Cuerno R, editors, Advances in Condensed Matter and Statistical Physics, New York: Nova Science Publishers.