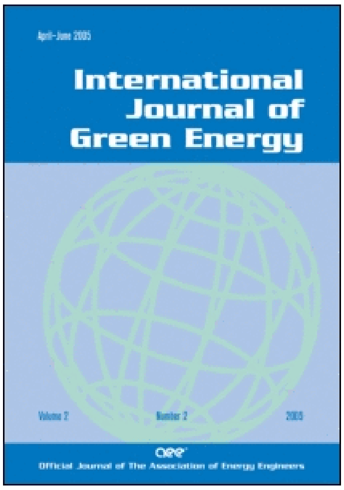


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# Introduction of the Carbon Tax Based on the Imputed Price of Carbon for the Post Kyoto Protocol Scenario

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# INTRODUCTION OF THE CARBON TAX BASED ON THE IMPUTED PRICE OF CARBON FOR THE POST KYOTO PROTOCOL SCENARIO

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***This paper proposes introduction of a carbon tax based on the imputed price of carbon (ICT) for the post Kyoto Protocol period considering the global participation and economic equity. Although the first commitment period is coming, climate change measures have made little progress due to the institutional defects of the Kyoto Protocol. To remedy such defects, a carbon tax is a suitable method. ICT is compared with the internationally common carbon tax using an applied general equilibrium model from environmental and economic perspectives. It is proven that ICT is a more appropriate method for the post Kyoto Protocol, considering the environmental and economic aspects simultaneously.***

**Keywords:** ***International climate change policy; Post Kyoto Protocol; Imputed price of carbon; Carbon tax; Economic equity***



## INTRODUCTION

Although the first commitment period of the Kyoto Protocol (2008–2012) is coming, climate change measures have made little progress globally and achievement of the quantitative goals of the Kyoto Protocol are still far for most of the Annex B countries ratifying the Kyoto Protocol. In addition, although it is indispensable to establish international climate change policies for the post Kyoto Protocol period as soon as possible to abate greenhouse gas (GHG) emissions and stabilize the climate, the related discussions have not been advanced, yet. Therefore, the policies for the post Kyoto Protocol period must be developed immediately to maintain the international efforts against climate change.

There have been a number of studies and proposals related to the post Kyoto Protocol scenario such as contraction and convergence (Mayer, 2000), the Brazilian proposal (Brazil, 1997), and a multi-stage approach (Den Elzen and Lucas, 2003; Criqui et al., 2003). Most of them insist that not only developed countries but also developing countries should make some efforts to abate GHG emissions on the basis of "common but differentiated responsibilities" (economic equity). However, conclusions on the methods for the post Kyoto Protocol have not yet been provided. Therefore, there is much room to discuss the measures.

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Under the circumstances, considering the necessity to abate GHG emissions on a global scale including developing countries, introduction of the carbon tax based on the imputed price of carbon (ICT) is proposed for the post Kyoto Protocol scenario in this paper.

The rest of this paper is organized as follows. Effectiveness of carbon tax as a climate change policy is indicated by pointing out the problems and the defects of the Kyoto Protocol and the Kyoto-type international climate change policies in the second section. The methods and the assumptions of the analysis are described in the third section. The results of the analysis are shown and discussed in the fourth section. Finally, the fifth section includes some concluding remarks with a brief discussion of the possibility of the policy mix with ICT and introduction of some additional climate change measures.

## INTRODUCTION OF CARBON TAX FOR THE POST KYOTO PROTOCOL SCENARIO



In this section, some problems and defects of the Kyoto Protocol and the Kyoto-type international climate change policies are discussed, then the availability of carbon tax, especially ICT, is indicated. The Kyoto-type international climate change policy is defined as a policy to abate GHG emissions by assigning a GHG emissions cap on each country and utilizing emissions trading for efficiency like the Kyoto Protocol.

Here, five problems or defects in the Kyoto Protocol and the Kyoto-type international climate change policies are pointed out[1]. First, the amount of GHG emissions (emissions cap) is assigned to the non-emitting entities, countries (governments), and not to the emitting entities such as industries, companies, and citizens in the Kyoto Protocol. Due to the system, since the emitting entities will do business as usual (or abate a small amount not to be damaged economically) unless governments regulate their emissions, it will be hard to achieve the quantitative goals. In fact, GHG emissions in most of the Annex B countries of the Kyoto Protocol have been continuously increasing since 1990 (UNFCCC, 2006) and the gap between the emissions and the targets is widening. Although it will be possible to achieve the targets if the assigned amount is allocated to all emitting entities internally, it is unfeasible and impossible because the number of such entities is tremendously large.

Next, developing countries are not obliged to abate GHG emissions under the Kyoto Protocol. According to Matsumoto (2006, 2007a, 2007c), introduction of climate change policies in developing countries is essential in order to realize effective and efficient emissions abatement. It is mentioned that lower energy efficiency, lower power generation efficiency, and higher GHG emissions per GDP in developing countries than those in developed countries are the reasons. For instance, $CO_2$ emissions per GDP in China are about ten times higher than those in Japan (Matsumoto, 2007a, 2007c). These studies also mention that not only developing countries but also economies in transition such as Russia have a possibility to play an important role in abating GHG emissions effectively and efficiently.

Third, it is considered that monopolistic power to supply emissions rights can be exercised in the international emissions trading market. Matsumoto (2007a, 2007b) analyzed the effect of the monopolistic power under the Kyoto Protocol. According to

[1]Park (2007) points out some problems on emissions trading and supports an international carbon tax.

the studies, there is a possibility that economies in transition exercise the monopolistic power and emissions abatement efficiency declines as a result. Therefore, climate change policies that can bring about such a problem must be avoided.

Next, there will be difficulty about negotiations to assign the amount of GHG emissions properly to each country if a Kyoto-type international climate change policy is established for the post Kyoto Protocol scenario. In fact, similar negotiation problems occurred under the Kyoto Protocol (Takamura and Kameyama, 2002), and a lot of the related negotiations proceeded with difficulty after the COP3 and became political issues (Hamanaka, 2006). Particularly if the framework is constructed to make economies in transition and developing countries participate in order to make it effective, it is expected that future negotiations will be much harder to convince them and balance with developed countries.

Finally, considering climate change policies from the viewpoints of quantitative methods such as emissions trading and price methods such as carbon tax of economic methods, in the case there is uncertainty about the marginal abatement cost, using quantitative methods is less efficient than using price methods if the gradient of the marginal benefit curve by abating emissions is more gentle than that of the marginal abatement cost curve (Weitzman theorem: Niizawa, 2002; Pizer, 1997; Weitzman, 1974). According to Pizer (1997), because damages due to climate change depend on atmospheric GHG stock rather than GHG emissions of each year, the effect of emissions abatement of each year on the marginal benefit is rather small. That is to say, carbon tax is superior to emissions trading as a climate change policy from the theoretical perspective.

As described above, since there are problems on the Kyoto Protocol and the Kyoto-type international climate change policies, introduction of carbon tax for the post Kyoto Protocol scenario is proposed in this paper. Also, it is indispensable to introduce carbon tax globally, including developing countries in consideration of the economic situations, in order to abate GHG emissions effectively and efficiently. Furthermore, unlike the Kyoto Protocol and the Kyoto-type international climate change policies, because the goal of carbon tax as an international climate change policy is just to introduce it as an internal policy, it will be easier for countries to achieve the goal determined internationally.

## METHODS FOR THE ANALYSIS

From the above section, it was suggested that the existing system was inappropriate and carbon tax had a great possibility as an international climate change policy. However, it is not obvious what kind of carbon tax is better to introduce on a global scale. Then, in this paper, ICT is compared with the carbon tax that imposes the common tax rate on all countries (CCT), which is the most efficient tax in theory.

In this section, first, the model and the assumptions for the analysis are described. Then, the meaning of ICT is described and the tax rates of both ICT and CCT used in the analysis are also shown.

### The Model and the Assumptions

In this study, the GTAP-E model (Burniaux and Truong, 2002), a static applied general equilibrium model, is used for the analysis. The model is constructed using Mathematica 5.2 of Wolfram Research Inc. The GTAP-E model is an extended version of the GTAP model (Hertel, 1996), and frameworks such as $CO_2$ emissions, emissions trading, and carbon tax are incorporated. Due to the structural condition of the model, $CO_2$ emissions out of GHG emissions are targeted in this analysis.

The latest version of the GTAP model, GTAP Version 6, is composed of 57 industrial sectors and 87 regions (and countries). However, if a 57 × 87 model was used, it would take considerable time to simulate and the fundamental outcomes of the study can be lost when investigating the results. Therefore, both the industrial sectors and the regions are aggregated into 10 as a compromise between the computation time and the adequacy of the analysis. Table 1 and Table 2 below show the structure of the industrial sectors and the regions adopted in the analysis respectively.

With regard to the data used in the analysis, because the GTAP-E model is based on the GTAP model as described, the economic data are from the GTAP database[2,3].

**Table 1** Structure of industrial sectors.

| Code | Member sectors |
|---|---|
| Energy sectors | |
| COA | coal |
| OIL | oil |
| GAS | natural gas |
| OLP | oil products |
| ELY | electricity |
| Non-energy sectors | |
| AGR | agriculture, forestry & fisheries |
| EIN | energy intensive industries (e.g. steel industry) |
| OIN | other industries (e.g. food processing) |
| TRP | transportations |
| SVC | other services (e.g. education) |

**Table 2** Structure of regions.

| Code | Member countries |
|---|---|
| Developed countries | |
| JPN | Japan |
| E_U | 15 EU countries (e.g. U.K.) |
| KPI | Other developed countries (e.g. Canada) |
| AUS | Australia |
| USA | United States |
| Economies in transition | |
| EFS | Economies in transition (e.g. Russia) |
| Developing countries | |
| CHN | China |
| IND | India |
| EEX | Energy exporting countries (e.g. Saudi Arabia) |
| ROW | Rest of the world (e.g. South Korea) |

[2]SeeDimaranan (2006) and https://www.gtap.agecon.purdue.edu/.

[3]The reference year of the GTAP Version 6 is 2001, thus the other data and studied year of the same year are applied in this study to fit it. Since the relative disparities among regions are important in this study although the post Kyoto Protocol is discussed, the year does not affect the essential significance of the discussions below.

**Table 3** $CO_2$ emissions of each region (Mt-C).

| Region | $CO_2$ emissions |
|---|---|
| JPN | 325.83 |
| E_U | 1030.08 |
| KPI | 210.53 |
| EFS | 886.82 |
| AUS | 112.82 |
| USA | 1759.82 |
| CHN | 1102.00 |
| IND | 334.81 |
| EEX | 1123.88 |
| ROW | 805.37 |

Concerning the $CO_2$ emissions data, they are calculated based on the energy consumption data from the GTAP database[4] using the method and the parameters of Houghton et al. (1997) and Lee (2002). Table 3 shows the $CO_2$ emissions of each region.



## Carbon Tax

The concept of the imputed price of carbon (or atmospheric $CO_2$ stock) in this study is to evaluate the value of carbon that is not traded and not priced in the market by the shadow price. It can be a climate change policy method and is derived from a global static optimization problem. In addition, unlike huge physical models which describe the details of causal relationships of climate change, it describes the causal relationships simplistically for policy discussions. ICT is the carbon tax based on this concept and calculated from Eq. (1) below[5]. The optimization problem and the derivation process of the equation are shown in appendix A.

$$t_r = \frac{\beta}{V - D}\left[\sum_r \frac{N_r y_r^{(1-\sigma)}}{1-\sigma}\right] y_r^{\sigma} \tag{1}$$

$t_r$: rate of ICT in region r (\$/t−C), $N_r$: population in region r, $y_r$: per capita net national income (NNI) in region r (\$), V: critical level of global atmospheric $CO_2$ stock (t-C), D: global atmospheric $CO_2$ stock (t-C). $\sigma$: elasticity parameter ($0 < \sigma < 1$), $\beta$: sensitivity parameter of utility against global atmospheric $CO_2$ stock ($0 < \beta < 1$).

As Eq. (1) indicates, since the rate of ICT of each region is proportional to per capita NNI exponentiated by elasticity parameter, the rates are higher in richer regions (developed countries) and lower in poorer regions (economies in transition and developing countries). Table 4 shows the parameter values used in Eq. (1). Also, Table 5 shows NNI, population, and per capita NNI of each region.

Then, Table 6 shows the rates of ICT of each region calculated from Eq. (1).

[4]See footnote 2.

[5]Since the tax rates are determined using the equation, it can function as a basis for the negotiations and will help them to progress more smoothly.

**Table 4** Parameter values in Eq. (1).

| Parameter | Value |
|---|---|
| β* | 0.1 |
| σ** | 0.927 |
| D (t−C)*** | 792.9 billion |
| V (t−C)* | 1.2 trillion |

*From Uzawa (1991).

**See appendix B.

***From Ad Hoc Committee of the International Strategy about Climate Change, Global Environment Division of Central Environmental Council (2005) and Marland et al. (2006).



**Table 5** NNI, population, and per capita NNI of each region.

| Region | NNI (Mil$)* | Population (thousand)** | Per capita NNI ($) |
|---|---|---|---|
| JPN | 3375317 | 126802 | 26618.80 |
| E_U | 6811926 | 376256 | 18104.50 |
| KPI | 997569 | 47079 | 21189.25 |
| EFS | 695305 | 387760 | 1793.13 |
| AUS | 299805 | 19426 | 15433.19 |
| USA | 8892100 | 277498 | 32043.84 |
| CHN | 1064500 | 1269909 | 838.25 |
| IND | 430440 | 1032127 | 417.04 |
| EEX | 2140180 | 1446053 | 1480.01 |
| ROW | 1861378 | 1149620 | 1619.12 |

*Calculated from United Nations (2003a, b). However, because the data of NNI for some regions is lacking, they are estimated from the regression equation of logarithm of NNI and gross national income (GNI, Mil$) in United Nations (2005). The regression equation is $\log(\text{NNI}) = 1.04 \times \log(\text{GNI}) - 0.63$, and the correlation coefficient is 0.99.

**From GTAP database (See for example https://www.gtap.agecon.purdue.edu/).

**Table 6** ICT of each region ($/t-C).

| Region | ICT |
|---|---|
| JPN | 451.54 |
| E_U | 315.83 |
| KPI | 365.44 |
| EFS | 37.00 |
| AUS | 272.37 |
| USA | 536.28 |
| CHN | 18.28 |
| IND | 9.57 |
| EEX | 30.97 |
| ROW | 33.66 |

As shown in Table 6, although the rates of ICT in developed countries are several hundreds of dollars per ton of carbon, those in developing countries are only several to several tens of dollars per ton of carbon.

In this study, ICT and CCT are evaluated from the viewpoints of changes in $CO_2$ emissions and GDP (environmental and economic influence respectively) and then compared.

Concerning the rate of CCT, it is set to make the model attain the equal change in global GDP to the case ICT is imposed as a result of the analysis. The rate of CCT corresponding to ICT in Table 6 is \$214.28/t−C. Comparing the two, because the rates of ICT exceed the rate of CCT only in developed countries, it is considered that the rate of CCT is extremely high for economies in transition and developing countries.

## RESULTS AND DISCUSSIONS



Fig. 1 and Fig. 2 show the changes in $CO_2$ emissions and GDP respectively as a result of the analysis.

As Fig. 1 indicates, 29.35% abatement of $CO_2$ emissions is brought about by ICT and 43.09% abatement is brought about by CCT globally. That is to say, CCT contributes about 1.5 times more to $CO_2$ emissions abatement than ICT. This is because tax rates higher than the average (from GDP change base), namely the rate of CCT, are imposed on developed countries and those lower than the average are imposed on economies in transition and developing countries under ICT. This means that the differences of marginal abatement costs among those groups and among the regions are rather large. As a result, overall, $CO_2$ emissions are abated inefficiently with ICT. On the other hand, because the tax rate is identical worldwide under CCT, marginal abatement costs are equalized throughout the world. Therefore, $CO_2$ emissions are abated rather efficiently and more abatement is realized.

Comparing the changes in GDP in Fig. 2, those by ICT and CCT in the world are equivalent, about −1.61%, due to the assumption of the analysis. However, looking at the

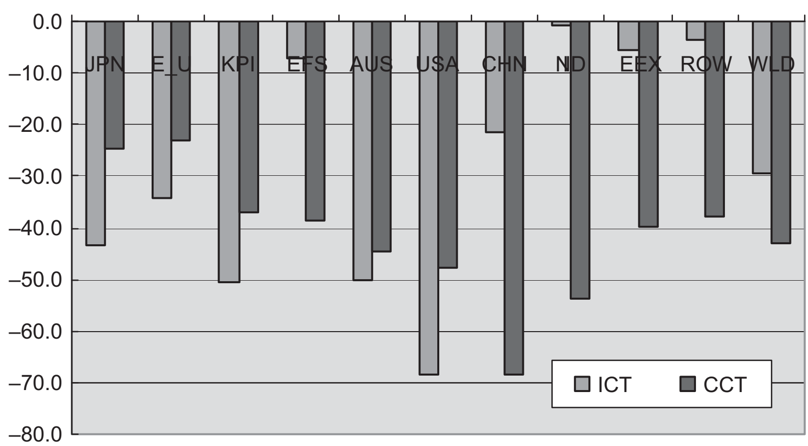


**Figure 1** Percentage changes in $CO_2$ emissions of each region *"WLD" means "worldwide" in this figure (it is same for figures below).

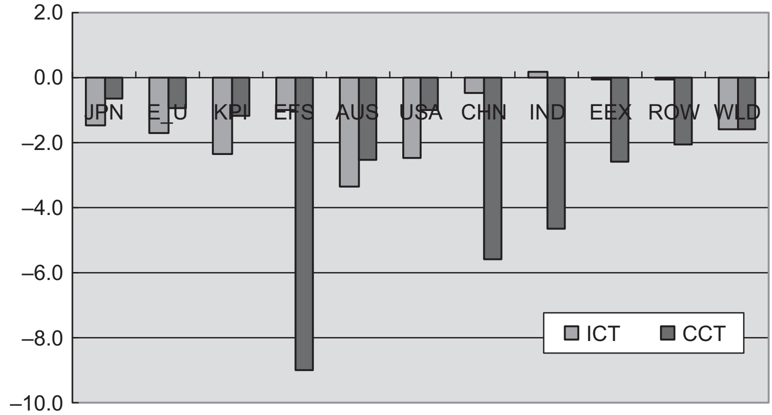


**Figure 2** Percentage changes in GDP of each region.



changes regionally, they indicate different tendencies. With regard to ICT, although a negative influence on GDP is observed in most regions, the damages on economies in transition and developing countries are smaller than those on developed countries (−2.05% in developed countries averagely, and −0.21% in economies in transition and developing countries averagely). In addition, positive influence is observed in IND, a developing country. Meanwhile, with regard to CCT, a negative influence is observed in all regions, and economies in transition and developing countries are damaged more than developed countries (−0.95% in developed countries averagely, and −3.69% in economies in transition and developing countries averagely).

Regarding the results above, CCT is certainly more appropriate than ICT as carbon tax from the environmental perspective. However, considering the economic aspects simultaneously, the suitability of CCT diminishes. That is to say, a tradeoff between economic equity and $CO_2$ emissions abatement effect occurs between ICT and CCT. Because CCT imposes excessive economic burdens on economies in transition and developing countries, it opposes the principle (Article 3) of UNFCCC, which says "The Parties should protect the climate system . . . on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities."[6] Moreover, there is a risk that economies in transition and developing countries would not to introduce such a worldwide carbon tax policy, CCT, due to the heavy burdens. If CCT is introduced without them, $CO_2$ emissions abatement efforts in developed countries will be canceled out to some extent due to carbon leakage in economies in transition and developing countries. Actually, as Fig. 3 shows, the changes in $CO_2$ emissions when CCT is imposed on developed countries but not on economies in transition and developing countries are increased in the regions where CCT is not imposed, although abated in developed countries. The rate of carbon leakage in this case is 16.38%. As a result, 14.72% abatement of $CO_2$ emissions, which is about a half of the case of ICT, is brought about.

[6]Looking at the recent discussions about international climate change policies such as COP, it is considered that both developed and developing countries recognized and agreed that this principle is crucial.

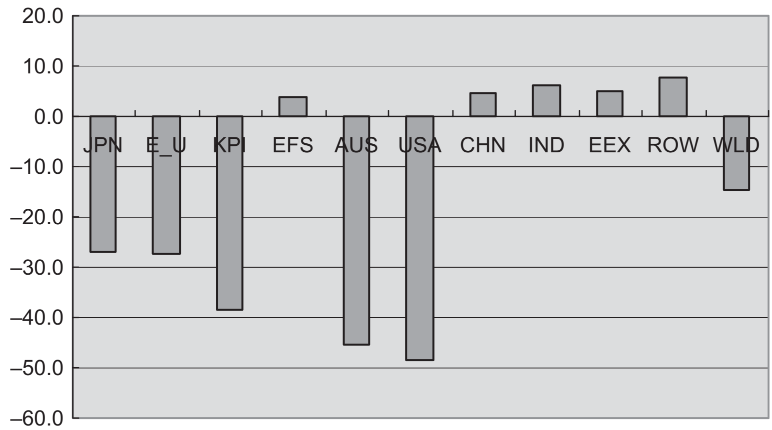


**Figure 3** Percentage changes in $CO_2$ emissions of each region when CCT is imposed on developed countries.



In contrast, because economies in transition and developing countries do not bear heavy economic burdens under ICT, there is economic equity among developed countries, economies in transition, and developing countries regarding their states of development[7]. Since economic issues are especially important for economies in transition and developing countries, and keeping the costs as low as possible raises the policy feasibility (Tol, 1999), methods to reduce economic burdens on these regions must be considered. Furthermore, concerning climate change decision making, deliberation of both environmental and economic consequences is important (Watson and the Core Writing Team, 2001). Therefore, taking into account the effectiveness of international climate change policies introduced on a global scale and the above discussions, there is higher feasibility that ICT can be introduced worldwide and $CO_2$ emissions abatement can be achieved as well although inferior to CCT.

Consequently, it is proven from the above analysis and discussions that ICT will be the appropriate policy method for the post Kyoto Protocol scenario.

## CONCLUSIONS

In this study, by pointing out the problems and the defects of the Kyoto Protocol and the Kyoto-type international climate change policies, a possibility of carbon tax as an international climate change policy for the post Kyoto Protocol was suggested. Through the analysis applying the GTAP-E model, ICT and CCT were compared from the viewpoints of the changes in $CO_2$ emissions and GDP. As a result, a tradeoff between economic equity and $CO_2$ emissions abatement effect was observed between ICT and CCT. Although ICT could achieve lower $CO_2$ emissions abatement than CCT, it was indicated that ICT was a more feasible international climate change policy considering the economic condition of each region and the significance of a policy introduced globally (the significance to avoid withdrawal of economies in transition and developing countries from the policy framework). That is, ICT is a feasible policy for the post Kyoto

[7]ICT also has a property that the tax rates can be revised flexibly according to the economic level as Eq. (1) indicates.

Protocol scenario. As all countries take part in the policy, it will link to further progress of the policy implementation for the future.

Because ICT is a price policy method, there is uncertainty about the $CO_2$ emissions abatement amount realized by a certain tax rate, unlike quantitative policy methods such as emissions trading. Therefore, in order to determine a tax rate, to realize a certain abatement amount, estimating the rate for example by simulation analysis using some models might be the only way. Also, in order to realize a certain abatement amount in practice, trial and error might be the only method to determine the tax rate as the Baumol-Oates tax (Baumol and Oates, 1971).

In the above discussion, it is assumed that ICT is introduced solely as the international climate change policy. However, there is a possibility to introduce it with other policy methods as policy mix to realize additional $CO_2$ emissions abatement. For example, by introducing the project-based $CO_2$ emissions abatement method, a system like CDM of the Kyoto mechanism, further abatement can be expected especially in developing countries where the potential to abate $CO_2$ emissions is higher (Matsumoto, 2006, 2007c). Furthermore, additional climate change measures such as technology transfer and financial aids especially for developing countries as implemented under the Kyoto Protocol and UNFCCC must be introduced simultaneously.

For the future study, it will be necessary to analyze dynamic effects of ICT, which I could not work due to the property of the model, by revising the model to deepen the discussions.



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## APPENDIX A: DERIVATION OF ICT (Eq. (1))

In this appendix, the derivation process of the imputed price of carbon, which is same as ICT expressed as Eq. (1), is described.

The global static optimization problem to derive Eq. (1) is formulated as follows (Matsumoto, 2007a).

$$\max \sum_r N_r u_r(y_r)\phi(D) \tag{2}$$

$$\text{s.t. } Y_r = N_r y_r \tag{3}$$

$$D_r = D_r(Y_r) \tag{4}$$

$$D = \sum_r D_r \tag{5}$$



$u_r(\cdot)$: standard utility function in region r (utility not considering the influence of climate change), $\phi(\cdot)$: environmental impact index function, $D_r(\cdot)$: atmospheric $CO_2$ stock function in region r, $Y_r$: NNI in region r ($), $D_r$: atmospheric $CO_2$ stock in region r (t-C).

Eq. (2) expresses the total utility of the world and negative influence on the utility due to the global atmospheric $CO_2$ stock is considered there. Eq. (3) expresses the condition about NNI of each region, Eq. (4) expresses the condition of the atmospheric $CO_2$ stock of each region, and Eq. (5) expresses the condition of the global atmospheric $CO_2$ stock.

Here, the standard utility functions $u_r(y_r)$ are the functions defined as $u_r(y_r) > 0$, $u_r'(y_r) > 0$, and $u_r''(y_r) < 0$ for all $y_r > 0$[8]. Also, the environmental impact index function $\phi(D)$ is the function defined as $\phi(D) > 0$, $\phi'(D) < 0$, and $\phi''(D) < 0$ for all $0 < D < V$.

The optimization problem is solved as follows.

The Lagrangian function L of the optimization problem is expressed as Eq. (6).

$$L = \sum_r N_r u_r(y_r)\phi(D) + \lambda(Y_r - N_r y_r) + \mu(D_r - D_r(Y_r)) + \rho\left(D - \sum_r D_r\right) \tag{6}$$

L: Lagrangian function, $\lambda$: Lagrange multiplier for Eq. (3), $\mu$: Lagrange multiplier for Eq. (4), $\rho$: Lagrange multiplier for Eq. (5).

Then, the first order condition of the optimization derived from Eq. (6) is expressed as Eq. (7)–Eq. (10).

$$\frac{\partial L}{\partial y_r} = N_r u_r'(y_r)\phi(D) - \lambda N_r = 0 \tag{7}$$

$$\frac{\partial L}{\partial Y_r} = \lambda - \mu D_r'(Y_r) = 0 \tag{8}$$

[8]A subscript "′" expresses derivative of the function.

$$\frac{\partial L}{\partial D_r} = \mu - \rho = 0 \tag{9}$$

$$\frac{\partial L}{\partial D} = \sum_r N_r u_r(y_r)\phi'(D) + \rho = 0 \tag{10}$$

Then, they can be rewritten as follows.

$$\lambda = u_r{}'(y_r)\phi(D) \tag{7$'$}$$

$$\mu = \frac{\lambda}{D_r{}'(Y_r)} = \frac{u_r{}'(y_r)\phi(D)}{D_r{}'(Y_r)} \tag{8$'$}$$

$$\rho = \mu = \frac{u_r{}'(y_r)\phi(D)}{D_r{}'(Y_r)} \tag{9$'$}$$

$$\rho = -\sum_r N_r u_r(y_r)\phi'(D) \tag{10$'$}$$

Then, Eq. (11) is obtained from Eq. (9′) and Eq. (10′).

$$\frac{u_r{}'(y_r)\phi(D)}{D_r{}'(Y_r)} = -\sum_r N_r u_r(y_r)\phi'(D) \tag{11}$$

Assuming that the economy is competitive and the rate $t_r$ of carbon tax is imposed in each region against the regional atmospheric $CO_2$ stock, this economy maximizes $Y_r - t_r D_r(Y_r)$. Therefore, NNI $Y_r$ is determined as Eq. (12) is satisfied.

$$\frac{\partial}{\partial Y_r}[Y_r - t_r D_r(Y_r)] = 1 - t_r D_r{}'(Y_r) = 0 \tag{12}$$

Eq. (12) can be rewritten as Eq. (12′).

$$t_r = \frac{1}{D_r{}'(Y_r)} \tag{12$'$}$$

Consequently, the rate of carbon tax of each region, Eq. (13), is obtained from Eq. (11) and Eq. (12′).

$$t_r = \frac{-\phi'(D)}{u_r{}'(y_r)\phi(D)} \sum_r N_r u_r(y_r) \tag{13}$$

Eq. (13) is the equation to calculate ICT. As Eq. (13) indicates, the rates of ICT are different among regions and they are proportional to the reciprocal of the marginal utility functions $u_r{}'(y_r)$.

In this study, the marginal utility functions $u_r'(y_r)$ are defined as Eq. (14).

$$u_r'(y_r) = y_r^{-\sigma} \tag{14}$$

Then, the standard utility functions $u_r(y_r)$ are obtained by integrating Eq. (14).

$$u_r(y_r) = \frac{y_r^{(1-\sigma)}}{1-\sigma} \tag{15}$$

Also, the environmental impact index function $\phi(D)$ is defined as Eq (16) (Uzawa, 1991).

$$\phi(D) = (V - D)^{\beta} \tag{16}$$

Eq. (16) expresses the degree of the influence on humankinds (decreases in utility) due to increases in the global atmospheric $CO_2$ stock. Then, by differentiating Eq. (16), the marginal environmental impact index function $\phi'(D)$ is obtained.

$$\phi'(D) = -\beta(V - D)^{(\beta-1)} \tag{17}$$

By substituting Eq. (14)-Eq. (17) into Eq. (11), the equation to calculate ICT in this study, Eq. (1), is obtained.

## APPENDIX B: DERIVATION OF ELASTICITY PARAMETER σ

The value of the elasticity parameter σ in Eq. (1) is determined as follows. As Eq. (1) indicates, the more the value approaches to 1, the more the rates of ICT approach a proportional relationship with per capita NNI $y_r$ among regions. On the contrary, the more the value approaches to 0, the less the differences of the tax rates among regions. Uzawa (1991) advocates a carbon tax system whose tax rates are proportional to $y_r$ of each region. It has characteristics similar to Eq. (1). Although the structure of the common parts among regions is different between Eq. (1) and Eq. (18) (see below), the difference of the structure of the differentiated part among regions is only whether σ is put or not. The larger the value, the more the relationships among regions between the two equations approach. Both of them has a same characteristic that the tax rates are higher in richer regions. Accordingly, the value of σ is determined based on Eq. (18) which calculates the rates of the carbon tax advocated in Uzawa (1991).

$$p_{rt} = \frac{1}{\delta + \gamma} \frac{\beta}{(V - D_t)} N y_{rt} \tag{18}$$

$p_{rt}$: rate of carbon tax based on Uzawa, 1991, (\$/t–C), N: world population, $D_t$: same as D (t-C), $y_{rt}$: same as $y_r$ (\$), δ: discount rate, γ: rate of $CO_2$ absorption by oceans.

Because Eq. (18) is derived from a dynamic model, a subscript t is put on some variables. However, it is not considered in this study since the model used in this study is static. Here, the value of σ is determined by equalizing the highest tax rate (the rate of USA) calculated from Eq. (1) and Eq. (18). Concerning the values of the parameters used in Eq. (18), δ = 0.05 and γ = 0.04 follow Uzawa (1991), and the others follow Table 4 and Table 5. Under these assumptions, σ = 0.927 is obtained.