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Article

Cost-Benefit Analysis of Adaptation to Beach Loss Due to Climate Change in Japan

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Abstract: To measure economic effects of changes in environmental quality caused by climate change in Japan, we estimate beach loss damage costs in Japan and in each prefecture and evaluate the economic effectiveness of hypothetical adaptation measures to restore sandy beaches. For analyses, we use a computable general equilibrium model (CGE) that integrates a utility function with environmental quality factors as an independent variable derived from a recreation demand function in a travel cost method (TCM). We use future projections of beach loss rates in 2081–2100 based on ensemble-mean regional sea-level rise (SLR) for four Representative Concentration Pathway (RCPs) scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5). The main findings of our study are presented as follows. (1) In 2081–2100, beach loss damage costs were estimated respectively as 398.54 million USD per year for RCP2.6, 468.96 (m.USD/year) for RCP4.5, 494.09 (m.USD/year) for RCP6.0, and 654.63 (m.USD/year) for RCP8.5. (2) For all RCPs, six prefectures for which the cost–benefit ratio exceeds 1.0 were Kanagawa, Osaka, Hyogo, Hiroshima, Saga, and Kumamoto. Our hypothetical adaptation measure of an artificial beach enhancement is expected to be quite effective as a public works project in these prefectures.

Keywords: adaptation; beach loss; climate change; computable general equilibrium model; travel cost method; cost benefit analysis

1. Introduction

According to the fifth Assessment Report (AR5) published by the IPCC [1], the medium-term and long-term countermeasures are expected to accommodate the possible impacts of climate change. The Ministry of the Environment (MOE) in Japan has discussed planning for a climate change adaptation policy. Some research projects in Japan such as S-8 [2] have forecast climate change effects by region and provide support for adaptative countermeasures. Assessment of climate change effects and the effectiveness of adaptation measures based on nationwide and regional climate change projection are needed.

Numerous attempts have been undertaken to evaluate the economic effects of climate change. Their evaluation methods are classifiable into two approaches: A partial equilibrium approach and a general equilibrium approach. The former method includes a travel cost method (TCM) and a contingent valuation method (CVM). These methods have been applied in some studies to quantify the economic value of the natural environment and ecosystems and the value of statistical life. Since these methods are partial equilibrium approaches, however, economic effects of changes in natural environment by climate change and environmental conservation policies on the whole economy cannot be captured. On the other hand, the latter method has a computable general equilibrium (CGE) analysis. Since a computable general equilibrium model explicitly formulates an objective function in economic agent, direct effects of climate change on economic activities of agent can be captured. In addition, since a CGE model treats all markets in the economy, indirect effects of climate change on the entire economy through changes in the behavior of agents can be captured. Using a CGE model, however, to measure the economic effects of climate change on the natural environment and ecosystems, formulation of the effects on them and estimation of their parameters in a model are necessary. As described above, numerous studies of economic evaluation of climate change have separately been analyzed by two approaches. Therefore, comprehensive assessments in a general equilibrium framework must be made through explicit linkage between a partial equilibrium approach and a general equilibrium approach.

By applying a recreation demand function to a general equilibrium model, for water reallocation issues in Nevada in the United States, Seung et al. [3] analyzed the effects of water reallocation on some recreation sectors and the agriculture sector. However, since the recreation demand function used in their study does not account for the generalized transportation cost, it is not consistent with a utility function. Ciscar et al. [4] comprehensively evaluated the economic and physical effects of climate change on the natural environment, ecosystem, and human society in Europe by treating four sectors as physical effect terms: Agriculture, coastal zone, flood, and tourism. Although their study produced estimates of respective physical effects from projected climate data under conditions of socioeconomic scenarios, and evaluated the projected economic effects by the economic model, it has no theoretical consistency between estimates of physical effect terms and economic models. In a general equilibrium analysis of waste problems in Japan, Miyata [5] derived a utility function consistent with a pre-formulated demand function from solving the integrability problem, and integrated externalities such as waste into a CGE model. For the sandy beach loss caused by climate change, Sakamoto and Nakajima [6] and Nakajima and Sakamoto [7] developed a CGE model that has a utility function consistent with a recreation demand function in a travel cost method by solving the integrability problem. Then, we extend the mode of describing the framework by Nakajima and Sakamoto [7] to simulate more realistic climate change scenarios.

In Japan, although numerous studies such as those of Mimura et al. [8] and Udo et al. [9] have been made of the physical effects of sea level rise and the beach loss caused by climate change, little is known about the economic effects of beach loss and adaptation strategies against climate change. From Table 1, Ohno et al. [10] and Sao et al. [11] evaluated recreation values for a sandy beach in Japan using a travel cost method. The former used beach loss rates calculated by Mimura et al. [8] and estimated the prefectural damage cost of a sandy beach. The latter used beach loss rates by Udo et al. [9], and evaluated not only the prefectural damage cost but also the effect of adaptation measures to restore a sandy beach. Since both studies were based on a partial equilibrium approach, they were unable to treat effects on prices and income caused by changes in environmental quality attributable to climate change. On the other hand, Sakamoto and Nakajima [6], Nakajima and Sakamoto [7], and Sao et al. [11] estimated beach loss damage costs attributable to climate change using a CGE model incorporating a utility function consistent with a recreation demand function in the travel cost method. However, since these studies used future projections by Mimura et al. [8], their economic assessments of beach loss became outdated. Although Sao et al. [11] evaluated adaptation measures for beach loss, their CGE model in these studies had only three goods: Composite goods, gasoline, and an expressway used to visit a sandy beach for recreation. As one might expect, their model framework was quite unrealistic.

Table 1. Comparison with damage costs reported from earlier studies.

Study				[10]	[6,7]	[11]	[12]	[13]	Our study
Method				TCM	CGE + TCM	CGE + TCM	TCM	CGE + TCM	CGE + TCM
Future projection				[8]	[8]	[8]	[9]	[9]	[14]
Climate model				–	–	–	MIROC5	3 models	21 models
Sea Level Rise	SLR: 30 cm		(A)	522	247	290	–	–	–
			(B)	56.6%	56.6%	26.5–97.0%	–	–	–
	SLR: 65 cm		(A)	753	440	530	–	–	–
			(B)	81.7%	81.7%	53.9–100.0%	–	–	–
	SLR: 100 cm		(A)	832	551	–	–	–	–
			(B)	90.3%	90.3%	–	–	–	–
(A) Damage cost/(B) Rate of coastal erosion	RCP2.6	2031–2050	(A)	–	–	–	254	116–147–184	–
			(B)	–	–	–	11.9–74.6%	11.9–74.6%	–
		2081–2100	(A)	–	–	–	426	335–402–440	399
			(B)	–	–	–	25.6–100.0%	25.6–100.0%	22.6–100.0%
	RCP4.5	2031–2050	(A)	–	–	–	–	142–150–197	–
			(B)	–	–	–	–	11.8–69.2%	–
		2081–2100	(A)	–	–	–	–	410–462–471	469
			(B)	–	–	–	–	28.0–100.0%	26.8–100.0%
	RCP6.0	2031–2050	(A)	–	–	–	–	–	–
			(B)	–	–	–	–	–	–
		2081–2100	(A)	–	–	–	–	–	494
			(B)	–	–	–	–	–	27.2–100.0%
	RCP8.5	2031–2050	(A)	–	–	–	284	174–179–252	–
			(B)	–	–	–	13.9–83.8%	13.9–83.8%	–
		2081–2100	(A)	–	–	–	494	615–644–644	654
			(B)	–	–	–	36.1–100.0%	36.1–100.0%	37.0–100.0%

Unit: 1 million USD/year.

Therefore, we sought to measure economic effects of changes in environmental quality attributable to climate change in Japan. Results were obtained using a CGE model that integrates a utility function with environmental quality factors as an independent variable derived from a recreation demand function in a travel cost method (TCM), we aim to estimate the damage cost of beach loss in each prefecture and in Japan and to evaluate the economic effectiveness of hypothetical adaptation measures to restore sandy beaches.

2. Methods and Data

2.1. Structure of Economic Model

We use the 2005 Input–Output table for Japan by MIC [15] as the reference dataset. Table 2 shows 30 sectors that we aggregated in our model. Economic influences comprise household, a production sector, an investment sector, government, and exports and imports.

2.1.1. Household

Figure 1 shows the consumption structure of household in our computable general equilibrium (CGE) model, where index R is used as household consumption for visiting a sandy beach and index H is used as household consumption excluding that for visiting a sandy beach. The set of all affordable bundles that satisfy a consumer's budget constraint is derived from solving the basic problem of utility maximization. Then, consumption of the petroleum and coal products and transportation for visiting a sandy beach depends on a recreation demand function that incorporates travel cost (the petroleum and coal price, the price of goods and services supplied by the transport sector, and the value of time) and the sandy beach area. For details of derivation of utility function consistent with recreation demand function and definition of goods for visiting a sandy beach, see Appendices A and B.

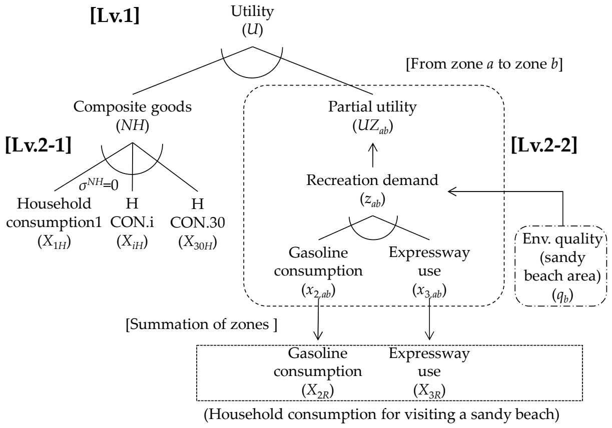


Figure 1. Structure of household.

2.1.2. Production Sector

Figure 2 shows that all production functions in the domestic production sector are assumed to have a nested function style. For the first step, labor L_j and capital K_j are aggregated into composite production factor VA_j using a Cobb–Douglas production function. As the second step, to produce the gross domestic output Y_j for the j-th production sector, the composite production factor is combined with intermediate inputs using a Leontief production function. In addition, the Cobb–Douglas production function allows us to describe substitution between labor L_j and capital K_j, while the Leontief production function does not between intermediate inputs X_{ij} and composite production factor VA_j [16].

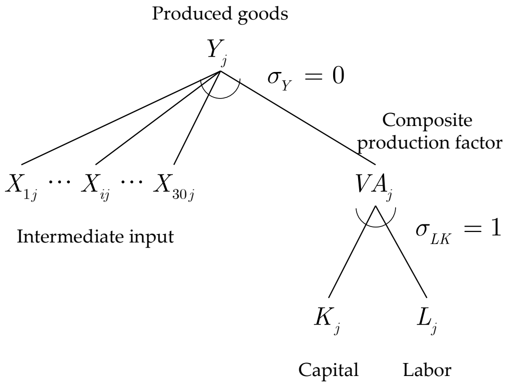


Figure 2. Structure of the production sector.

Table 2. Sector classification.

	Sector	Code		Sector	Code
1	Agriculture	AGR	16	Information and communication equipment	ICE
2	Forestry	FRS	17	electronic components	ELC
3	Fishery	FSH	18	Transportation equipment	TRE
4	Mining	MIN	19	Precision instruments	PRI
5	Foods	FOD	20	Other manufacturing products	OMF
6	Textile and paper products	TEX	21	Construction	CNS
7	Chemical products	CPR	22	Electricity	ELY
8	Petroleum refinery products	PET	23	Commerce	COM
9	Coal products	COL	24	Finance and insurance	FIN
10	Ceramic, stone and clay products	CER	25	Real estate	EST
11	Iron and steel	IRN	26	Transport	TRP
12	Non-ferrous metals	NFM	27	Facility service for road transport	RTP
13	Metal products	MTL	28	Public administration	PBA
14	General machinery	MCH	29	Accommodations	ACM
15	Electrical machinery	ELM	30	Other services	SRV

2.1.3. Government Sector and Investment Sector

The government sector and investment sector are assumed to have behaviors modeled by Hosoe et al. [16]. The government earns revenues from an income tax, production tax, and indirect tax. Then, the government spends them on purchases of goods proportionately with the constant expenditure share. The structure of investment sector is the same as that of the government sector. In accordance with Hosoe et al. [16], the investment agent collects funds from the household, the government, and the foreign sector. Then, this virtual agent purchases investment goods proportionately with a constant share.

2.1.4. Export and Import

In accordance with Hosoe et al. [16], Figure 3 portrays the structure of the substitution between imports and domestic goods and that of the transformation between exports and domestic goods. Regarding imperfect substitution between imports and domestic goods, we adopt Armington's assumption [17]. The *i*-th Armington-composite-good-producing sector aggregates domestic goods D_i and imports IM_i into composite goods Q_i using a constant elasticity of substitution (CES) function. However, gross domestic output Y_i is transformed into domestic goods D_i and exports EX_i using a constant elasticity of transformation (CET) function. Both parameters of elasticity of transformation σ_{DEX} and elasticity of substitution σ_{DIM} are assumed to be 2.0 exogenously.

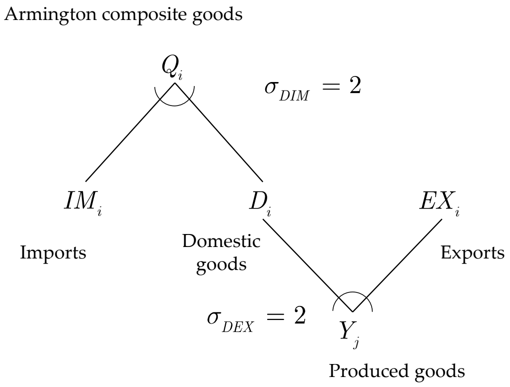


Figure 3. Structure of exports and imports.

2.2. *Setting of Scenarios*

2.2.1. Scenario of Beach Loss Caused by Climate Change

We use the results of the future projections of beach loss in Japan by Udo and Takeda [14] as the Beach loss scenario. Udo and Takeda [14] calculated the beach-loss rates in 2081–2100 relative to the reference period 1986–2005 based on ensemble-mean regional sea-level rise (SLR) for four Representative Concentration Pathway (RCPs) scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) using 21 models of the Coupled Model Intercomparison Project Phase 5 (CMIP5). We specifically examine four scenarios in 2081–2100 based on ensemble mean SLR, and use 21 scenarios for uncertainty assessment using 21 models of CMIP5 (ACCESS 1.0, BCC CSM 1.1, CanESM2, CNRM CM5, CSIRO3.6.0, NOAA GFDL-ESM2M, NOAA GFDL-ESM2G, GISS-E2-R, HadGEM2-CC, HadGEM2-ES, INM-CM4, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MRI_CGCM3, NorESM-ME, NorESM1-M). In addition, Table 3 presents the minimum and maximum beach loss rates in each prefecture in our beach loss scenarios. Table 4 and Figure 4 show 47 prefectures in Japan.

Table 3. Future projections of beach loss rate in Japan by Udo and Takeda (2017).

	RCP2.6	RCP4.5	RCP6.0	RCP8.5	21 Models
Mean [min., max.]	66.9 [22.6, 100.0]	75.5 [26.8, 100.0]	77.5 [27.2, 100.0]	88.5 [37.0, 100.0]	76.5 [28.8, 100.0]

Table 4. 47 prefectures in Japan.

	Prefecture	Code		Prefecture	Code		Prefecture	Code
1	Hokkaido	HKD	17	Ishikawa	ISK	33	Okayama	OKY
2	Aomori	AMR	18	Fukui	FKI	34	Hiroshima	HRS
3	Iwate	IWT	19	Yamanashi	YMN	35	Yamaguchi	YGC
4	Miyagi	MYG	20	Nagano	NGN	36	Tokushima	TKS
5	Akita	AKT	21	Gifu	GIF	37	Kagawa	KGW
6	Yamagata	YGT	22	Shizuoka	SZK	38	Ehime	EHM
7	Fukushima	FKS	23	Aichi	ACH	39	Kochi	KOC
8	Ibaraki	IBR	24	Mie	MIE	40	Fukuoka	FKO
9	Tochigi	TCG	25	Shiga	SIG	41	Saga	SAG
10	Gunma	GNM	26	Kyoto	KYT	42	Nagasaki	NGS
11	Saitama	STM	27	Osaka	OSK	43	Kumamoto	KMT
12	Chiba	CHB	28	Hyogo	HYG	44	Oita	OIT
13	Tokyo	TKY	29	Nara	NAR	45	Miyazaki	MYZ
14	Kanagawa	KNG	30	Wakayama	WKY	46	Kagoshima	KGS
15	Niigata	NGT	31	Tottori	TTR	47	Okinawa	OKW
16	Toyama	TYM	32	Shimane	SMN			

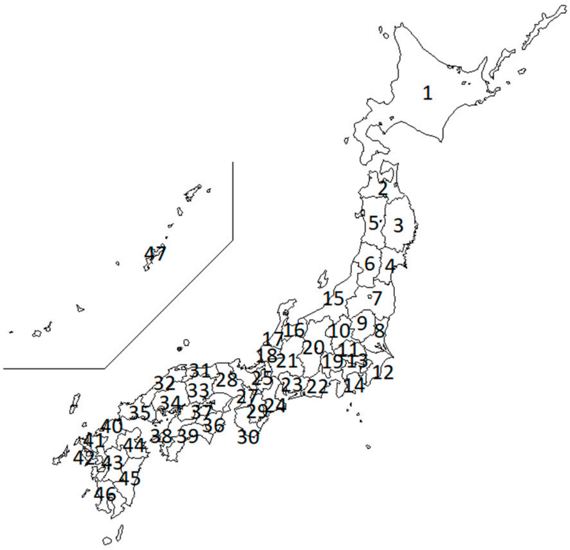


Figure 4. 47 prefectures in Japan.

2.2.2. Scenario of Adaptation Measure for Restoring Sandy Beach

For hypothetical adaptation measures related to beach loss, we assume that after erosion of coastal areas caused by the sea-level rise, the coastal area can be restored to its earlier state by implementation of adaptation measures such as a public works project using artificial beach enhancement. From considerations of data availability and comparison with earlier studies, we chose to use an average adaptation cost per unit area assumed by Sao et al. [12] for the scenario of adaptation measures for restoring sandy beaches. Sao et al. [12] collected data including those of 92 public works in 33 prefectures related to artificial beach enhancement, and assumed the average adaptation cost per unit area as 215.96 USD/m^2 from available data for sandy beaches. However, since few public works projects are limited to artificial beach enhancement and since these projects include costs of protecting land unrelated to sandy beaches, it is noteworthy that the average adaptation cost that we assumed might be overestimated.

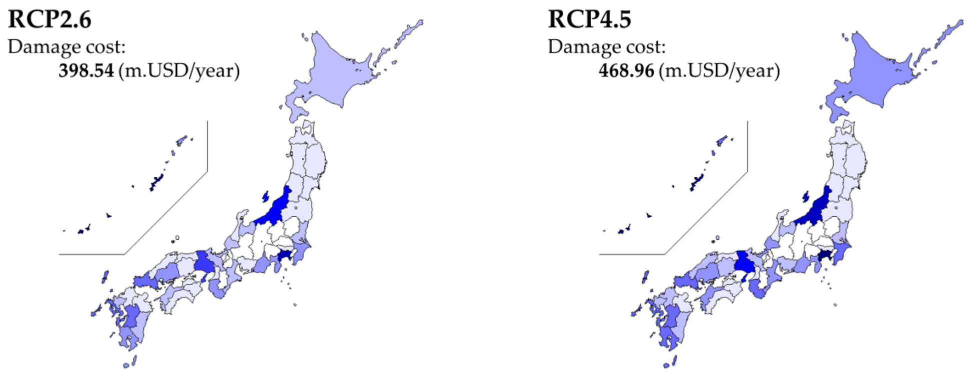
Finally, to estimate beach loss damage costs and to evaluate the economic effectiveness of hypothetical adaptation measures to restore sandy beaches, we measure the benefit as equivalent variation. For details of the definition of benefit, see Appendix C.

3. Results and Discussion

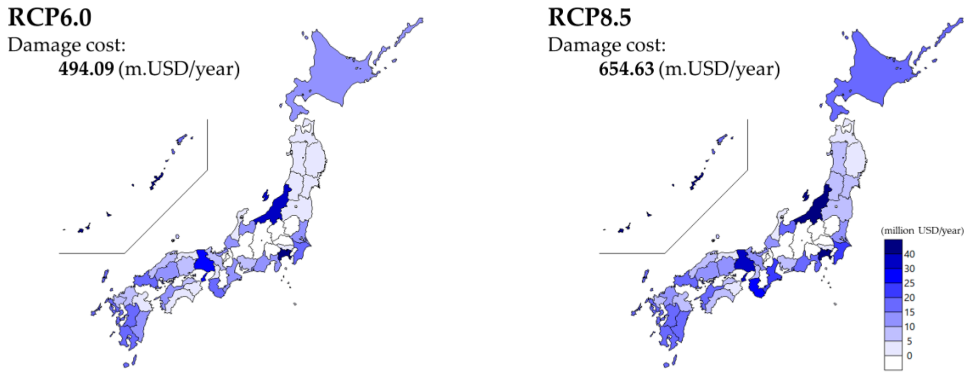
3.1. Economic Effects of Beach Loss

Figure 5 shows damage costs presented by the projected beach loss for RCP2.6, RCP4.5, RCP6.0, and RCP8.5 in 2081–2100. These figures indicate that the higher the future temperature becomes, the more the damage cost of sandy beach increases. In 2081–2100, damage costs are estimated respectively as 398.54 million USD per year for RCP2.6, 468.96 (m.USD/year) for RCP4.5, 494.09 (m.USD/year) for RCP6.0, and 654.63 (m.USD/year) for RCP8.5.

Figure 5 and Table 5 present prefectural damage costs because of the projected beach loss in four RCPs in 2081–2100. For any RCPs, damage costs of four prefectures (Okinawa, Kanagawa, Niigata and Hyogo) accounts for about 40% to about 45% of the total damage cost to Japan. As shown in Table 5, for RCP2.6, damage costs of these four prefectures were estimated respectively as 22.85 million USD per year to 87.42 (m.USD/year). For RCP8.5, four prefectural damage costs are estimated as 33.87 (m.USD/year) to 87.42 (m.USD/year).



(**a**) RCP2.6 (**b**) RCP4.5



(**c**) RCP6.0 (**d**) RCP8.5

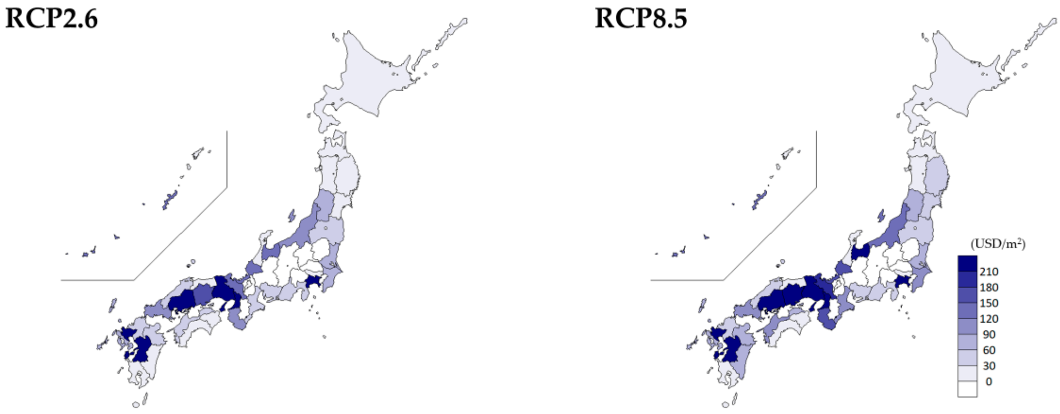
Figure 5. Prefectural damage costs attributable to beach loss in four representative concentration pathway (RCPs) scenarios in 2081–2100 (**a**–**d**).

Table 5. Prefectural damage costs attributable to beach loss in four RCPs in 2081–2100.

	Pref.	RCP2.6	RCP4.5	RCP6.0	RCP8.5		Pref.	RCP2.6	RCP4.5	RCP6.0	RCP8.5
1	HKD	9.74	12.05	12.53	17.13	25	SIG	0.00	0.00	0.00	0.00
2	AMR	1.44	1.75	1.78	2.52	26	KYT	5.50	7.03	7.73	12.26
3	IWT	2.22	2.86	2.91	4.13	27	OSK	2.88	3.52	3.67	5.59
4	MYG	2.66	3.03	3.12	5.01	28	HYG	22.85	25.93	27.33	33.87
5	AKT	2.36	3.01	3.13	5.11	29	NAR	0.00	0.00	0.00	0.00
6	YGT	3.12	3.89	4.07	6.31	30	WKY	12.94	17.98	18.61	26.42
7	FKS	2.35	2.91	3.09	5.56	31	TTR	0.49	0.65	0.65	0.95
8	IBR	6.83	9.26	10.32	13.97	32	SMN	4.19	5.35	5.59	9.26
9	TCG	0.00	0.00	0.00	0.00	33	OKY	4.24	5.65	5.72	12.23
10	GNM	0.00	0.00	0.00	0.00	34	HRS	14.56	14.56	14.56	14.56
11	STM	0.00	0.00	0.00	0.00	35	YGC	15.99	15.99	15.99	15.99
12	CHB	11.27	15.41	17.37	24.70	36	TKS	1.18	1.50	1.61	2.44
13	TKY	0.76	1.14	1.18	1.41	37	KGW	3.80	4.56	5.04	9.37
14	KNG	39.29	53.50	62.11	87.32	38	EHM	7.80	11.30	12.37	15.24
15	NGT	26.84	31.01	31.82	51.45	39	KOC	1.68	2.45	2.70	5.55
16	TYM	6.64	9.55	10.12	18.92	40	FKO	3.77	5.55	6.31	10.63
17	ISK	1.96	2.60	2.80	4.13	41	SAG	7.17	7.17	7.17	7.17
18	FKI	9.87	10.98	11.37	13.55	42	NGS	15.01	16.20	16.20	16.20
19	YMN	0.00	0.00	0.00	0.00	43	KMT	15.47	15.47	15.47	15.47
20	NGN	0.00	0.00	0.00	0.00	44	OIT	2.89	3.59	3.84	6.94
21	GIF	0.00	0.00	0.00	0.00	45	MYZ	6.13	9.21	11.29	17.47
22	SZK	10.46	12.33	12.92	17.82	46	KGS	11.51	15.37	15.77	18.42
23	ACH	4.61	5.72	6.04	8.17	47	OKW	87.42	87.42	87.42	87.42
24	MIE	8.64	11.52	12.39	23.97		Total	398.54	468.96	494.09	654.63

Unit: 1 million USD/year.

Figure 6 and Table 6 show prefectural damage costs per unit area attributable to beach loss in four RCPs in 2081–2100. Prefectures for which the damage cost per unit area is high were Kanagawa, Niigata, Toyama, Fukui, Kyoto, Osaka, Hyogo, Wakayama, Okayama, Hiroshima, Saga, Kumamoto, and Okinawa. Especially, damage costs per unit area in prefectures in western Japan or along the Inland Sea tend to be higher. For RCP2.6, damage costs per unit area to the tenth highest prefecture were Saga, Kumamoto, Kanagawa, Osaka, Hiroshima, Hyogo, Okayama, Okinawa, Fukui, and Toyama in order from the highest, estimated as 138.47 USD per unit area to 723.26 (USD/m^2). For RCP8.5, damage costs per unit area to the tenth prefecture were Kanagawa, Saga, Kumamoto, Osaka, Okayama, Hyogo, Toyama, Hiroshima, Kyoto, and Wakayama, estimated as 178.34 to 765.76 (USD/m^2).



(**a**) RCP2.6 (**b**) RCP8.5

Figure 6. Prefectural damage costs per unit area for RCP2.6 (**a**) and RCP8.5 (**b**) in 2081–2100.

Table 6. Prefectural damage costs per unit area in four RCPs in 2081–2100.

	Pref.	RCP2.6	RCP4.5	RCP6.0	RCP8.5		Pref.	RCP2.6	RCP4.5	RCP6.0	RCP8.5
1	HKD	6.55	7.10	7.22	8.51	25	SIG	0.00	0.00	0.00	0.00
2	AMR	6.44	6.55	6.57	6.86	26	KYT	136.12	145.50	150.02	183.80
3	IWT	26.39	29.88	30.14	38.27	27	OSK	409.10	427.33	431.78	493.81
4	MYG	26.42	27.28	27.49	32.53	28	HYG	232.02	248.90	256.99	298.80
5	AKT	15.22	16.23	16.43	20.11	29	NAR	0.00	0.00	0.00	0.00
6	YGT	68.91	72.43	73.33	85.12	30	WKY	101.59	126.07	129.48	178.34
7	FKS	30.83	32.94	33.63	45.50	31	TTR	6.12	6.31	6.31	6.68
8	IBR	62.21	65.01	66.29	70.93	32	SMN	41.06	44.47	45.23	58.68
9	TCG	0.00	0.00	0.00	0.00	33	OKY	174.81	198.67	200.03	360.31
10	GNM	0.00	0.00	0.00	0.00	34	HRS	239.17	239.17	239.17	239.17
11	STM	0.00	0.00	0.00	0.00	35	YGC	92.55	92.55	92.55	92.55
12	CHB	77.40	82.50	85.07	95.61	36	TKS	12.77	14.08	14.56	18.88
13	TKY	4.87	5.55	5.64	6.11	37	KGW	50.85	54.11	56.31	81.33
14	KNG	487.64	556.09	602.93	765.76	38	EHM	54.72	71.38	77.32	94.63
15	NGT	102.64	107.68	108.68	137.01	39	KOC	8.41	9.83	10.36	18.45
16	TYM	138.47	164.64	170.42	285.88	40	FKO	31.19	36.80	39.53	59.50
17	ISK	14.80	15.82	16.15	18.59	41	SAG	723.26	723.26	723.26	723.26
18	FKI	139.76	146.55	149.00	163.71	42	NGS	78.75	84.96	84.96	84.96
19	YMN	0.00	0.00	0.00	0.00	43	KMT	560.73	560.73	560.73	560.73
20	NGN	0.00	0.00	0.00	0.00	44	OIT	39.67	43.50	45.00	68.39
21	GIF	0.00	0.00	0.00	0.00	45	MYZ	29.87	36.44	41.77	61.63
22	SZK	41.93	43.40	43.88	48.12	46	KGS	15.40	18.74	19.13	21.86
23	ACH	40.00	42.51	43.26	48.73	47	OKW	148.66	148.66	148.66	148.66
24	MIE	45.14	51.76	53.97	92.82		Total	57.59	59.63	61.24	70.62

Unit: USD/m^2.

For uncertainty assessment, we calculated 21 beach loss scenarios in 2081–2100 using 21 CMIP5 models. For RCP4.5, damage costs were estimated respectively as an average of 491.06 million USD/year, a minimum of 385.72 (m.USD/year), and a maximum of 739.50 (m.USD/year). In addition,

Figure 7 shows prefectural damage costs per unit area using 21 CMIP5 models. As shown in Figure 7, although results of Kanagawa and Toyama have a large variance, those of many other prefectures have a small variance.

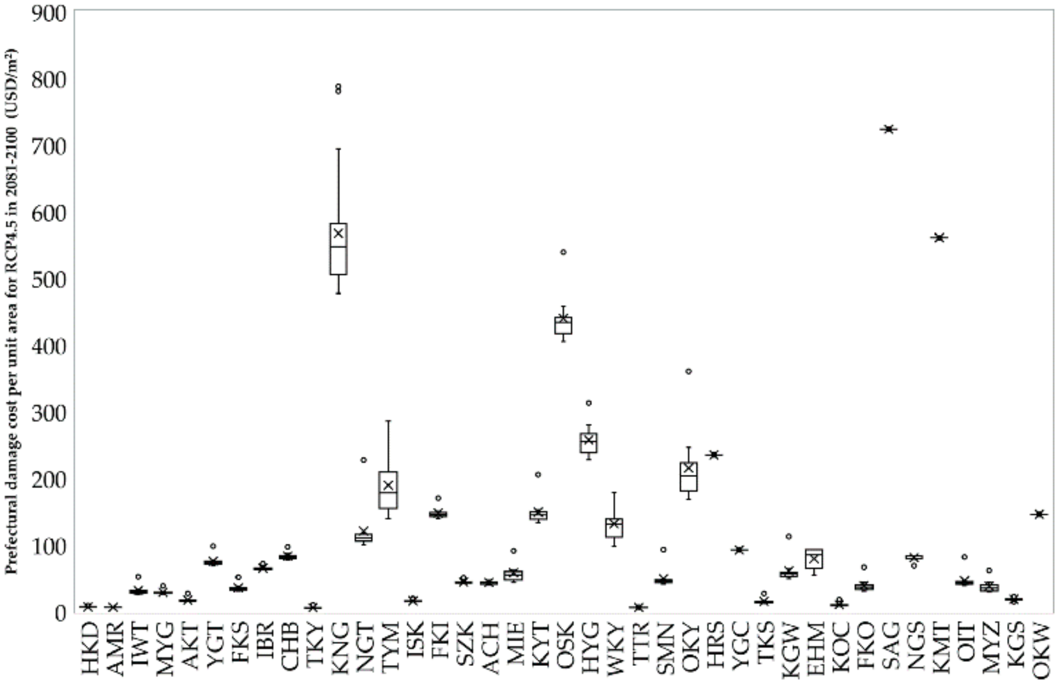
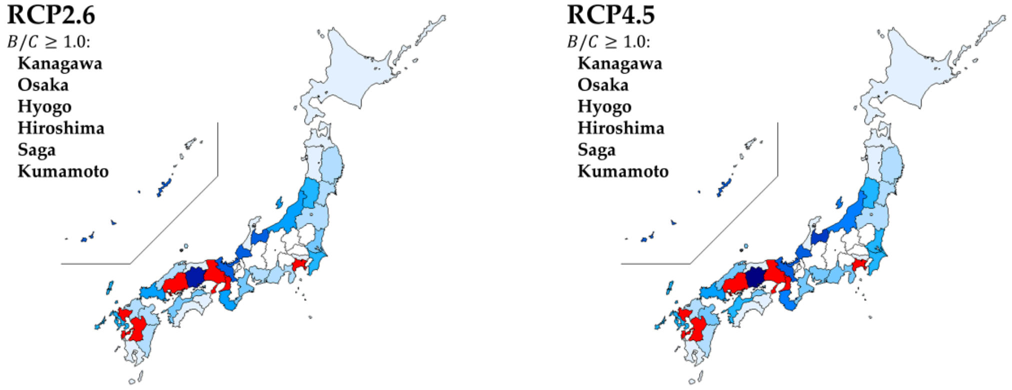


Figure 7. Prefectural damage cost per unit area using the beach loss rates calculated by 21 CMIP5 models.

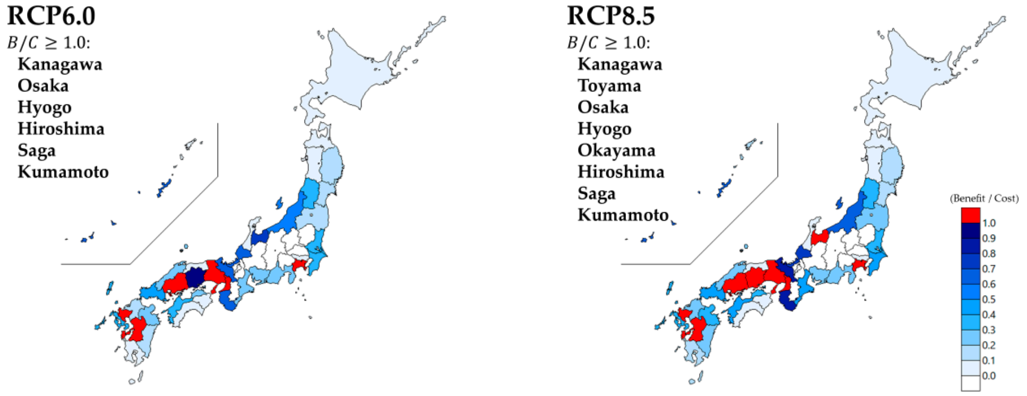
3.2. Cost–Benefit Analysis of Adaptation Policy

Figure 8 and Table 6 show cost–benefit ratios of adaptation policies for RCP2.6, for RCP4.5, for RCP6.0, and for RCP8.5 in 2081–2100. Prefectures in red in Figure 8 and shaded values in Table 6 have cost–benefit ratios larger than 1.0, i.e., the benefit from adaptation measures exceeds the cost because of beach loss. As described above, we assumed 215.96 USD/m^2 of the average cost per unit area as the adaptation cost to restore a sandy beach. The higher the future temperature becomes, the more numerous the prefectures for which adaptation measures are cost-effective become. Especially in four prefectures along the Inland Sea, which are Osaka, Hyogo, Okayama, and Hiroshima, our hypothetical adaptation measure as a public works project of artificial beach enhancement is quite effective.

For RCP2.6, six prefectures for which the cost–benefit ratio exceeds 1.0 were Kanagawa, Osaka, Hyogo, Hiroshima, Saga, and Kumamoto. In contrast, for RCP8.5, eight prefectures with a cost–benefit ratio over 1.0 were Kanagawa, Toyama, Osaka, Hyogo, Okayama, Hiroshima, Saga, and Kumamoto.



(**a**) RCP2.6 (**b**) RCP4.5



(**c**) RCP6.0 (**d**) RCP8.5

Figure 8. Cost–benefit ratios of adaptation policies in four RCPs in 2081–2100.

3.3. Discussion

We compare the results of beach loss damage costs attributable to climate change with those of earlier studies. As shown in Table 1, Ohno et al. [10], Sakamoto and Nakajima [6], Nakajima and Sakamoto [7], and Sao et al. [11] used the future projection of beach loss calculated by Mimura et al. [8] and estimated the damage costs of sandy beach because of the sea level rise from 30 to 100 cm. These earlier studies estimated damage costs of the sea level rise as 247 to 832 (m.USD/year). It is apparent that the results of our study are slightly lower than those of earlier studies. Especially, although differences between results of Ohno et al. [10] and our study are larger, it is likely that these results became overestimated since Ohno et al. [10] formulated damage costs of beach loss by a proportional relation between the frequency of visiting the sandy beach for recreation and the sandy beach area.

Sao et al. [12] and Nakajima et al. [13] used the future projection of beach loss by Udo et al. [9] and respectively estimated damage costs for RCP2.6 and RCP8.5. Sao et al. [12] estimated them as 254–284 (m.USD/year) in 2031–2050 and 426–494 (m.USD/year) in 2081–2100. One reason for the difference between results reported by Sao et al. [12] and those of our study is that our general equilibrium approach reflects price changes and income changes that are not considered in the definition of consumer surplus derived from the partial equilibrium approach. Consequently, it is apparent that beach loss damage costs in our study are slightly lower than those found in earlier studies.

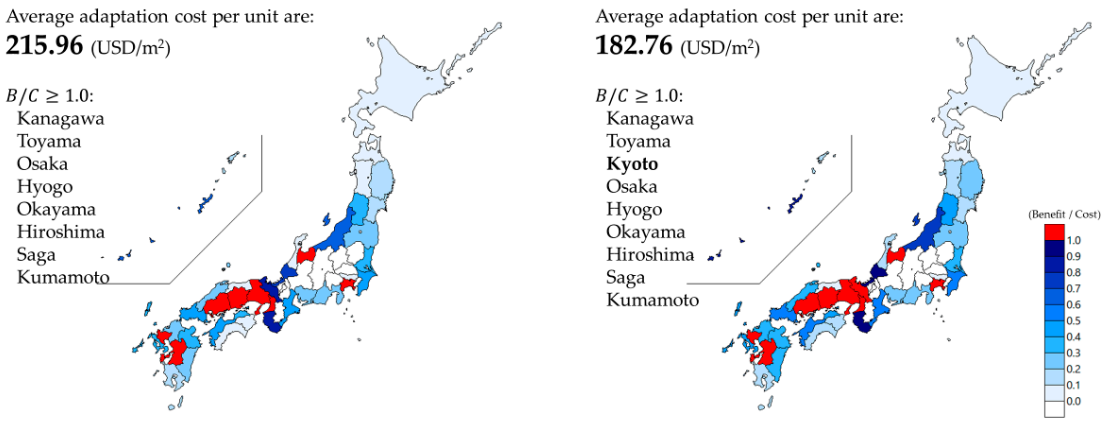
Table 7 shows the number of prefectures for which the cost–benefit ratio exceeds 1.0 in the adaptation scenarios using 215.96 and 182.76 USD/m^2 as the average cost per unit area. Although the number of cost-effective prefectures between Sao et al. [11] and Sao et al. [12] is significantly different, Sao et al. [12] described that the difference between these studies resulted from the average adaptation cost per unit area. As described above, for the possibility that the average adaptation cost per unit area (215.96 USD/m^2) that Sao et al. [12] assumed could be overestimated, we compared the effects of two adaptation costs. In both adaptation scenarios, the number of prefectures for which adaptation measures were cost–effective in our results was almost identical for all RCPs. Consequently, it is apparent that the results of our study are more robust than those of earlier studies. In addition, six prefectures for which the cost-benefit ratio exceeds 1.0 for all RCPs have a large damage cost despite the small area of their beaches. In other words, we consider the higher damage cost per unit area to be the reason why hypothetical adaptation measures are economically efficient.

Table 7. Comparison with numbers of cost-effective prefectures of earlier studies.

Study		[11]	[12]	[13]			Our study
Method		CGE + TCM	TCM	CGE + TCM			CGE + TCM
Future projection		[8]	[9]	[9]			[14]
Climate model		–	MIROC5	MIROC5	MRI-CGCM3	HadGEM2-ES	21 models
Average adaptation cost (USD/m^2)		182.76	215.96	215.96/182.76			215.96/182.76
SLR: 30 cm		17	–	–	–	–	–
SLR: 65 cm		20	–	–	–	–	–
RCP2.6	2031–2050	–	2	4/4	4/4	4/4	
	2081–2100	–	1	6/7	5/5	6/6	6/6
RCP4.5	2031–2050	–	–	4/4	4/4	4/4	–
	2081–2100	–	–	6/8	6/6	6/7	6/7
RCP6.0	2031–2050	–	–	–	–	–	–
	2081–2100	–	–	–	–	–	6/7
RCP8.5	2031–2050	–	2	4/4	4/4	4/4	–
	2081–2100	–	1	8/9	8/9	8/9	8/9

Unit: The number of cost-effective prefectures.

Figure 9 portrays effects of two adaptation measures of RCP8.5 in 2081–2100. As described above, we demonstrated that the higher the future temperature becomes, the greater the number of prefectures for which adaptation measures are cost–effective. From Figure 9, the lower adaptation cost makes adaptation measures in Kyoto more effective. Additionally, one assumes that the adaptation cost becomes much lower, then we can say that adaptation measures in Niigata, Wakayama, Fukui, and Okinawa are potentially cost-effective. Therefore, it is apparent that the lower the average adaptation cost per unit becomes, the more numerous prefectures for which the adaptation measures are cost–effective become. Especially, in some prefectures along the Inland Sea such as Osaka, Hyogo, Okayama, and Hiroshima, our hypothetical adaptation measure of a public works project of an artificial beach enhancement is quite effective.



(**a**) The average adaptation cost per unit area: 215.96 (USD/m^2)

(**b**) The average adaptation cost per unit area: 182.76 (USD/m^2)

Figure 9. Comparison of cost–benefit ratios of two adaptation scenarios for RCP8.5 in 2081–2100.

4. Conclusions

To assess the economic effects of changes in environmental quality caused by climate change in Japan, we used a computable general equilibrium model that integrates a utility function with environmental quality factors as independent variables derived from a recreation demand function in a travel cost method. Results show the estimated damage costs of beach loss in Japan and in the respective prefectures. We evaluated the economic effectiveness of hypothetical adaptation measures to restore sandy beaches. The findings obtained from this study are presented below.

1. Higher future temperatures will cause higher damage costs of sandy beaches. In 2081–2100, we estimated damage costs as 398.54 million USD per year for RCP2.6, 468.96 (m.USD/year) for RCP4.5, 494.09 (m.USD/year) for RCP6.0, and 654.63 (m.USD/year) for RCP8.5, respectively.
2. For all RCPs, six prefectures for which the cost–benefit ratio exceeds 1.0 were Kanagawa, Osaka, Hyogo, Hiroshima, Saga, and Kumamoto.
3. Higher future temperatures will bring high numbers of prefectures for which adaptation measures are cost–effective. Especially for four prefectures along the Inland Sea, which are Osaka, Hyogo, Okayama, and Hiroshima, our hypothetical adaptation measure of an artificial beach enhancement is expected to be quite effective as a public works project.

Further examinations can be expected to support further discussion. First, since we were unable to treat the adaptation cost endogenously, we will incorporate endogenous adaptation costs into our CGE model and evaluate the effectiveness of some adaptation measures. Secondly, since we evaluated only the recreation value (use value) estimated using TCM, we expect to develop a CGE model incorporating evaluation methods of non-use values.

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Appendix A. Derivation of Utility Function Consistent with Recreation Demand Function

In accordance with Nakajima and Sakamoto [7], we present the expression for a utility function from a recreation demand function estimated using the zone travel cost method, and apply it to a computable general equilibrium model.

First, we assume that some regions are divided into N zones. Each zone has a natural environment, which is a sandy beach in our study. In addition, a recreation demand function from zone a to zone b is estimated using regression analysis as shown below. For elimination of negative estimation of visiting rate and treatment of heteroskedasticity attributable to different populations among zones, we employ a semi-logarithmic function. For details, see Cooper and Loomis [18].

$$\ln\left(\frac{z_{ab}}{n_a}\right) = \hat{\gamma}_0 + \hat{\gamma}_1 p_{ab} + \hat{\gamma}_2 q_b + \hat{\varepsilon}_{ab}, \ \forall a,b \tag{A1}$$

$$p_{ab} \equiv \frac{p_2^Y g_{ab} + p_3^Y c_{ab} + w t_{ab}}{p^{NH}}, \ \forall a,b \tag{A2}$$

In Equations (A1) and (A2), z_{ab} denotes the frequency of visits from zone a to zone b; n_a represents the population in zone a. (z_{ab}/n_a) signifies the visitation rate from zone a to zone b. Therein, p_{ab} represents the travel cost per visit necessary to make a round trip from zone a to zone b. It is defined as a relative price of composite goods price p^{NH} in Equation (A2). For it, $p_{ab} = p_{ba}$. Then, p_2^Y, p_3^Y, and w respectively denote the price of the petroleum and coal products sectors, the price of goods and services supplied by the transport sector, and the value of time as described below. Furthermore, g_{ab}, c_{ab}, and t_{ab}, respectively represent the amount of gasoline per visit, expressway use per visit, and time per visit. Furthermore, q_b signifies the natural environmental quality in zone b, which is a sandy beach in this study. By formulating the natural environmental quality as an explanatory variable explicitly, we can make a computable general equilibrium analyses by changes in environmental quality. In Equation (A2), $\hat{\gamma}_0$, $\hat{\gamma}_1$, and $\hat{\gamma}_2$ are estimated parameters. They are $\hat{\gamma}_1 < 0$ and $\hat{\gamma}_1 > 0$; $\hat{\varepsilon}_{ab}$ is a residual.

Since a demand function is derived from solving a utility maximization problem of household, a utility function exists corresponding to its demand function. This is known as an integrability problem. For details related to the integrability problem, one can consult works by Varian [19], Mas-Colell et al. [20], and Jehle and Reny [21]. By solving the integrability problem, a utility function with Equation (A1) as a recreation demand function and a budget constraint are derived as shown below.

$$u_a = x_a + \frac{1}{\hat{\gamma}_1} \sum_b z_{ab} (\ln z_{ab} - \ln \Gamma_{ab} - 1), \ \forall a \tag{A3}$$

$$p^{NH} x_a + \sum_a \left(p_2^Y g_{ab} + p_3^Y c_{ab} \right) z_{ab} = M_a, \ \forall a \tag{A4}$$

$$\Gamma_{ab} \equiv n_a \exp\left\{ \hat{\gamma}_0 + \hat{\gamma}_1 \left(\frac{w t_{ab}}{p^{NH}} \right) + \hat{\gamma}_2 q_b + \hat{\varepsilon}_{ab} \right\}, \ \forall a, b \tag{A5}$$

In those equations, u_a denotes household utility in zone a, x_a represents consumption of composite goods in zone a, and M_a is the household income in zone a. Additionally, Γ_{ab} signifies the number of visitors from zone a to zone b when the price of gasoline and toll fees between zone a and zone b equal zero ($p_2^Y = p_3^Y = 0$). If $\hat{\gamma}_1 < 0$, then it is $z_{ab} \leq \Gamma_{ab}$ in subjective equilibrium of household. The second term of the right-hand side in Equation (A3) is non-negative. For simplification, since our model relies on the assumption that there exists only a single household, a utility function and budget constraint are formulated by the summation of each variable with respect to the zone in Equations (A3) and (A4), as:

$$U = NH + \frac{1}{\hat{\gamma}_1} \sum_a \sum_b z_{ab} (\ln z_{ab} - \ln \Gamma_{ab} - 1) \tag{A6}$$

$$p^{NH} NH + \sum_a \sum_b \left(p_2^Y g_{ab} + p_3^Y c_{ab} \right) z_{ab} = M \tag{A7}$$

where U represents utility ($= \sum_a u_a$), NH denotes consumption of composite goods ($= \sum_a x_a$), and M signifies income ($= \sum_a M_a$) in household.

Parameters of a recreation demand function are estimated using the function form shown in Equation (A1). Ohno et al. [10] created a dataset with travel cost and the amount of traffic for visiting a sandy beach from MAFF [22] database and estimated parameters of a recreation demand function. Furthermore, environmental quality data are created as a logarithmic value of the sandy beach area by prefecture estimated by Mimura et al. [8]. Then, we employ the same data set as Ohno et al. [10] and the environmental quality data and estimate the parameters of our recreation demand function using the least-square method. Table A1 presents the estimated parameters. Since regression coefficients of travel cost are estimated as negative and since the coefficient of environmental quality is positive, the sign condition is satisfied. In addition, all variables were found to be significant. It is apparent that the coefficient of environmental quality is less than 1, and that the frequency of visits decreases gradually as the sandy beach area decreases. However, Ohno et al. [10] assumed that changing the sandy beach area changes the frequency of visits proportionally.

Table A1. Estimated parameters in the utility function.

Coefficient	Estimated Value	*t*-Value
γ_0	−4.604	−7.575
γ_1	-4.110×10^{-4}	−14.029
γ_2	0.329	3.178
$\overline{R}^2$	0.477	
No. of observations	227	

Appendix B. Definition of Goods for Visiting a Sandy Beach

Let $x_{2,ab}$ represent gasoline consumption and $x_{3,ab}$ be the use of expressway needed to travel between zone a and zone b. Furthermore, the frequency of visiting them is denoted by z_{ab} in independent variables of the utility function. The relations among them can be expressed as shown below.

$$x_{2,ab} = g_{ab} \cdot z_{ab}, \ \forall a, b \tag{A8}$$

$$x_{3,ab} = c_{ab} \cdot z_{ab}, \ \forall a, b \tag{A9}$$

Equations (A8) and (A9) can be shown as optimal solutions in a cost minimization problem based on a production function with the Leontief technology as presented below.

$$z_{ab} = \min\left\{\frac{x_{2,ab}}{g_{ab}}, \frac{x_{3,ab}}{c_{ab}}\right\}, \ \forall a, b \tag{A10}$$

From Equation (A10), it is apparent that a household *produces* a visit for a recreation site, and that Equation (A10) is a part of the utility function. It is presented as UZ_{ab} in Figure 1.

Secondly, gasoline consumption and expressway use by a household are aggregated with respect to all zones, respectively, as Equations (A11) and (A12).

$$X_{2H} = \sum_a \sum_b x_{2,ab} \tag{A11}$$

$$X_{3H} = \sum_a \sum_b x_{3,ab} \tag{A12}$$

According to MIC [19], gasoline is produced in the "petroleum refinery" sector. The use of an expressway is produced in the "travel agency and other services related to the transport" sector, in the input–output table for Japan, which comprises 190 sectors. We assume that hypothetical sectors produce gasoline and expressways to visit a sandy beach.

Since we estimate parameters in a recreation demand function using travel cost data for Japan and annual traffic data among all prefectures, we can measure the annual gasoline consumption and a use of expressway to visit a sandy beach in a money metric by using these data. The annual gasoline consumption for visiting a sandy beach is divided from household consumption of the petroleum refinery products in the input–output table. Additionally, intermediate inputs and factor inputs in the petroleum refinery sector are divided at the same rate as household consumption. Similarly, we treat the annual use of an expressway for visiting a sandy beach. Other production sectors are aggregated as the composite goods sector. In summary, our model has three goods and sectors that include gasoline consumption for visiting a sandy beach, use of an expressway for visiting a sandy beach, and composite goods.

Appendix C. Definition of Benefit

Travel cost methods measure consumer surplus CS from Equation (A1) to evaluate natural environments economically. Actually, CS is proportional to the sum of the frequency of visits as shown below. In addition, $\mathbf{p}^Y = \left(p_1^Y, p_2^Y, p_3^Y\right)$ is a price vector; $\mathbf{q} = (q_1, \cdots, q_N)$ is an environmental quality vector.

$$CS\left(\mathbf{p}^Y, \mathbf{q}\right) \equiv \sum_a \sum_b \int_{p_2^Y g_{ab} + p_3^Y c_{ac} + w t_{ab}}^{\infty} n_a \exp\left\{\hat{\gamma}_0 + \hat{\gamma}_1\left(\frac{l}{p^{NH}}\right) + \hat{\gamma}_2 q_b + \hat{\varepsilon}_{ab}\right\} dl = -\frac{p^{NH}}{\hat{\gamma}_1} \sum_a \sum_b z_{ab} \quad \text{(A13)}$$

In general, when environmental quality changes in $\mathbf{q}^0 \to \mathbf{q}^1$ in a travel cost method, from $\Delta CS = CS\left(\mathbf{p}^{Y0}, \mathbf{q}^1\right) - CS\left(\mathbf{p}^{Y0}, \mathbf{q}^0\right)$, the change in an environmental quality is evaluated by price $\mathbf{p}^{Y0}$ fixed in the initial period. Although this evaluation method is a simple process, without fixing a price vector, the benefit by change in environmental quality should be measured by considering changes in the price vector. We aim at measuring benefits by considering changes in price and income.

We assume that we define the benefit as equivalent variation (EV). Since the indirect utility function converts the sum of the factor income and the consumer surplus into a composite goods term, it can be expressed as shown below.

$$V\left(\mathbf{p}^Y, M, \mathbf{q}\right) = \frac{M + CS\left(\mathbf{p}^Y, \mathbf{q}\right)}{p^{NH}} \quad \text{(A14)}$$

Since the expenditure function is an inverse function of the indirect utility function with respect to income, it can be derived from solving for M, where V represents utility.

$$E\left(\mathbf{p}^Y, V, \mathbf{q}\right) = p^{NH} \cdot V - CS\left(\mathbf{p}^Y, \mathbf{q}\right) \quad \text{(A15)}$$

We assume that the beach loss causes changes in the sandy beach area of $\mathbf{q}^0$ to $\mathbf{q}^1$. From the perspective of general equilibrium analysis, such a change in the exogenous variable affects prices and factor incomes. With this beach loss, it is assumed that the price system changes from $\mathbf{p}^{Y0}$ to $\mathbf{p}^{Y1}$, and that the factor income changes from M^0 to M^1. Then, the equivalent variation is shown as presented below.

$$\begin{aligned} EV &= E\left(\mathbf{p}^{Y0}, V\left(\mathbf{p}^{Y1}, M^1, \mathbf{q}^1\right), \mathbf{q}^0\right) - E\left(\mathbf{p}^{Y0}, V\left(\mathbf{p}^{Y0}, M^0, \mathbf{q}^0\right), \mathbf{q}^0\right) \\ EV &= p^{NH0} \cdot \left[\frac{M^1 + CS\left(\mathbf{p}^{Y1}, \mathbf{q}^1\right)}{p^{NH1}} - \frac{M^0 + CS\left(\mathbf{p}^{Y0}, \mathbf{q}^0\right)}{p^{NH0}}\right] \end{aligned} \quad \text{(A16)}$$

Next, to define a prefectural equivalent variation, we rewrite Equation (A13) by the summation with respect to zone a in Equation (A13) as follows.

$$CS_b\left(\mathbf{p}^Y, \mathbf{q}\right) \equiv \sum_a \int_{p_2^Y g_{ab} + p_3^Y c_{ac} + w t_{ab}}^{\infty} n_a \exp\left\{\hat{\gamma}_0 + \hat{\gamma}_1\left(\frac{l}{p^{NH}}\right) + \hat{\gamma}_2 q_b + \hat{\varepsilon}_{ab}\right\} dl = -\frac{p^{NH}}{\hat{\gamma}_1} \sum_a z_{ab} \quad \text{(A17)}$$

We rewrite Equation (A16) using Equation (A17). We define the prefectural equivalent variation in zone b as shown below.

$$\begin{aligned} EV_b &= E_b\left(\mathbf{p}^{Y0}, V\left(\mathbf{p}^{Y1}, M^1, \mathbf{q}^1\right), \mathbf{q}^0\right) - E_b\left(\mathbf{p}^{Y0}, V\left(\mathbf{p}^{Y0}, M^0, \mathbf{q}^0\right), \mathbf{q}^0\right) \\ EV_b &= p^{NH0} \cdot \left[\left(\frac{M^1}{p^{NH1}} - \frac{M^0}{p^{NH0}}\right) - \frac{1}{\hat{\gamma}_1}\left\{\sum_a \left(z_{ab}^1 - z_{ab}^0\right)\right\}\right] \end{aligned} \quad \text{(A18)}$$

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