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RESEARCH ARTICLE

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Increase in carbon prices: analysis of energy-economy modeling

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Abstract This study examines the mechanisms of social cost of carbon (SCC) and marginal abatement cost (MAC) in climate change modeling. To examine these mechanisms, we observed the shifts in the marginal benefit (MB) and marginal cost (MC) curves of carbon dioxide (CO_2) abatement when parameter values are changed. In the observation, we used the DICE model proposed by Nordhaus (A question of balance: weighing the options on global warming policies. Yale University Press, New Haven, 2008) changing 24 parameters for the observation. In consequent, firstly, we have found that discount rate is not only one of the parameters which significantly raise the carbon price, that is, other parameters may have significant impact too. Secondly, we have found that there are two patterns in the rise of the SCC, and three patterns in the rise of the MAC. Thirdly, we have found that the difference between the rise of the SCC and MAC is primarily caused by the horizontal MB curve in CO_2 emissions reduction; an upward shift of MC curve raises MAC but never raises the SCC. Thus, the choice of the SCC or MAC may make the change of carbon price different, affecting global warming policy.

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1 Introduction

Reduction of carbon dioxide (CO_2) emission comes with both costs and benefits—the benefit of avoided costs inherent in climate change. In the 1990s, policy makers primarily focused on the costs of specific emission reduction requirements, using marginal abatement cost (MAC) as an evaluation mechanism. Current policy discussions, however, focus increasingly on balancing costs and benefits. While the social cost of carbon (SCC) has been discussed in the academic world since the 1990s, this concept has only recently captured policy makers' interests.

Technically, the SCC denotes the net present value (NPV) of the impact on climate change by an additional ton of carbon being emitted into the atmosphere. The SCC is derived from a cost-benefit analysis using an integrated economic-environmental model. The MAC is defined as the cost of reducing carbon emissions by an additional one ton to achieve a specific abatement goal. The MAC is derived from a cost-effectiveness analysis using the integrated economic-environmental model. It should be noted that at the SCC point, the values for both SCC and MAC become equal, that is, the two mechanisms overlap under certain circumstances. While the SCC is gaining more attention, it does not necessarily mean that the SCC is being accepted as a policy goal. For example, the Kyoto Protocol and the Post-Kyoto negotiations adopt the MAC-based cost-effectiveness approach. Therefore, it is important to understand both the SCC and MAC for climate policy considerations.

A number of studies estimate the SCC and MAC through energy-economy models. However, their estimates are study dependent, and it is difficult to find a price consensus among researchers. Significant SCC research has been conducted that consolidates the price range (see Fankhauser and Tol 1997; Tol 2005). Kuik et al. (2009) summarized the price range for the MAC. Tol (2005) and Kuik et al. (2009) conducted regression analyses for the existing SCC and MAC estimates, selecting factors that determine carbon prices. While there may be several causes for carbon price variation, parameter setting is often the major one. The Stern Review (Stern 2007), for example, showed that a high SCC can be a consequence of setting a low discount rate. This paper conducts a parameter sensitivity analysis of the SCC and MAC, finding parameters that increase carbon prices as well as mechanisms that result in the increase of these prices.

The SCC and MAC sensitivity analysis is not novel. Nordhaus (1994) and Gerlagh and van der Zwaan (2004), for example, conducted sensitivity analyses on the SCC and MAC, respectively. These studies show the factors increase carbon prices. However, the mechanisms of this carbon price increase have not yet been fully investigated. To examine this phenomena, the marginal benefit and cost curves similar to that of Pizer (2002) addressed the debate on price versus quantity control in climate change policy.

Carbon prices are arrived at by determining the net of the marginal benefit (MB) minus the marginal cost (MC) of CO_2 emission reduction.[1] The intersection of the MB and MC curves represents the SCC (see Fig. 1). The MAC is bounded by the MC curve and is primarily dependent on the exogenous goal of CO_2 emission reduction, yielding the implicit damage function in the model. Moreover, because of the above difference, the parameters that increase the SCC and MAC as well as the mechanisms that increase the carbon prices differ.

As a simplistic notion, there are two SCC increase mechanisms, as shown in Fig. 1[2]: one is an upward shift in the MB curve, and the other is an upward shift in the MC curve. The SCC increase mechanisms, however, are different from those shown in Fig. 1. This study analyzes the SCC and MAC increase mechanisms and the resulting shift of the MB and MC curves when parameter values are changed. The findings of these analyses contribute to the consideration of the SCC or MAC as appropriate for policy formulation.

Section 2 reviews previous studies' estimates of the SCC and MAC, and compares the time profiles of their values. Section 3 conducts a sensitivity analysis of the SCC using the Dynamic Integrated Model of Climate and the Economy (DICE) model proposed by Nordhaus (2008) to shed light on the mechanisms of SCC increase. Section 4 presents the sensitivity analysis of the MAC, conducting an observation similar to that in Sect. 3. Section 5 concludes.

2 Literature review

This section reviews the SCC and MAC over time. We find time sequence patterns of the two carbon prices in existing studies as well as the relationship between the MAC and the emission reduction rate.

2.1 Social cost of carbon (SCC)

The SCC represents the NPV of the impact on climate change of an additional ton of carbon emitted into the atmosphere. In energy-economy models, the SCC is calculated using the cost-benefit approach, which maximizes the total net benefit by avoiding climate damage. Within a cost-benefit approach, benefits are accrued by avoiding damages. The SCC is computed along the optimal emissions control trajectory. On reaching 100 % emission control, the SCC continues to account for the incremental damage caused because of the emission of an incremental unit of CO_2, while the MAC decreases with the rate of technical progress in the backstop technology.

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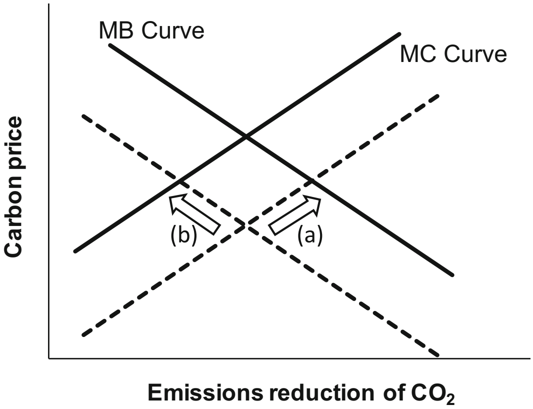
[1] "MC" is used to distinguish the marginal cost curve from the "MAC"; throughout the paper "MC" is used to denote the marginal cost curve and "MAC" is used to denote the marginal abatement cost.

[2] In this paper, we use the term "mechanism" from the perspective of the MB-MC curves.

Fig. 1 Two possible mechanisms of the SCC increase: Price increase by an upward shift of the MB and MC curves



A number of SCC studies have been conducted subsequent to the pioneering work of Nordhaus (1982). Those studies' values are summarized in Fankhauser and Tol (1997), and subsequently in Clarkson and Deyes (2002), Pearce (2003), Watkiss et al. (2006), and Tol (2005, 2008). In contrast to the recent studies of Tol (2005, 2008) in reviewing current SCC values, we focus on the differences between the SCC and MAC over time.

Figures 2, 3 and Table 1 summarize the SCC estimates reviewed by Tol (2008). Figure 2 shows the SCC frequency distribution, and Fig. 3 shows the cumulative SCC frequency. The figures indicate that approximately 50 percent of the estimated values are below 40 $/tC, and about 80 percent are below 100 $/tC. Table 1 shows the basic statistics for the estimated SCC across the entire sample and selected subsamples. The table clearly indicates that high estimates are driven by the choice of discount rate, and the SCC estimates get smaller as the publication date progresses.

Figure 4 summarizes the SCC over time, as estimated in the literature. For 2005, the GDP deflators in The World Economic Outlook (IMF 2010) were used to adjust for the different SCC estimates. The SCC estimates range between 7.5 and 172 $/tC in 1991–2000, and are expected to rise to 70–216 $/tC in 2091–2100. There are three outliers among the estimated values in Table 2 and Fig. 4: the upper values of Cline (1992), which reported 172 $/tC in 1991–2000 and is estimated at 306 $/tC in 2021–2030; the mean values according to the PAGE model, in Watkiss et al. (2006), which reported 74 $/tC in 1991–2000 and is estimated to be 164 $/tC in 2021–2030; and the uncertainty case of Newbold et al. (2010), which is estimated at 180 $/tC in 2021–2030. Ranges of these values are presented because Cline (1992) uses a zero utility discount rate, while the mean value of Watkiss et al. (2006) and the uncertain case of Newbold et al. (2010) uses Monte–Carlo simulations. When we exclude these three outliers, the values are estimated to be approximately 50 $/tC in 2000 and 200 $/tC in 2100. It is said that under arbitrage conditions, the SCC increases roughly over time at the prevailing rate of interest (e.g., IPCC 2007 p. 652), and the time paths of the SCC in Fig. 4 roughly follow this rule.[3]

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[3] This rule is called the Hotelling rule. It (in this case, the SCC increases at the rate of interest over time) only holds under specific circumstances to be specified.

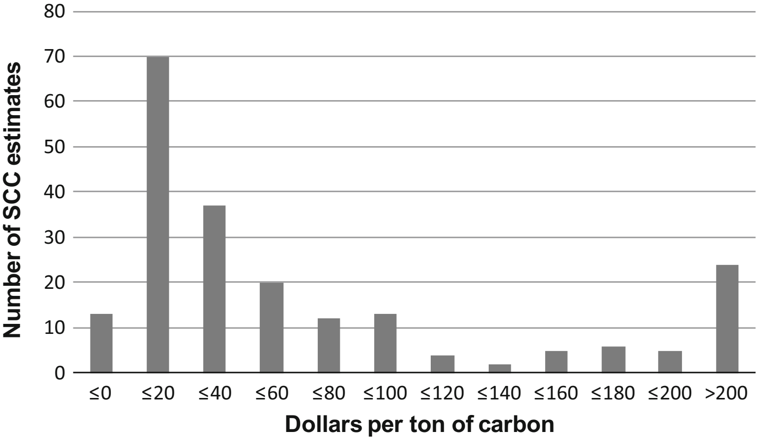

Fig. 2 Frequency distribution of the SCC ($/tC). Source: adapted from Tol (2008)

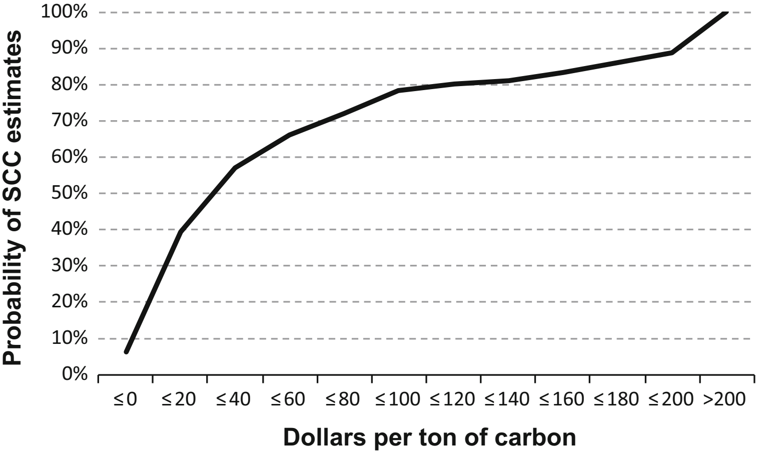

Fig. 3 Cumulative frequency distribution (probability) of the SCC ($/tC). Source: adapted from Tol (2008)

2.2 Marginal abatement cost (MAC)

The MAC refers to the cost incurred for reducing emissions by an additional ton of carbon to achieve a specific emission goal. In energy-economy models, the MAC is usually calculated using the cost-effectiveness approach, which maximizes/minimizes the NPV of total utility/total cost, respectively, given a certain emission goal. It should be noted that the MAC can also be calculated along an optimal trajectory of emission reduction. Under the cost-effectiveness approach, the MAC is expressed as the carbon tax necessary to achieve the emission goal. The SCC is

Table 1 Selected characteristics of the joint probability density of the SCC for the whole sample (all) and selected subsamples ($/tC)

	All	Pure time preference rate			Publication date		
		0 %	1 %	3 %	<1996	1996–2001	>2001
Mode	35	129	56	14	36	37	27
Mean	127	317	80	24	190	120	88
Std Dev	243	301	70	21	392	179	121
90-percentile	267	722	171	51	397	274	196
95-percentile	453	856	204	61	1,555	482	263

Mode, mean, standard deviation, 90-percentile, 95-percentile. Solely the data of “Fisher-Tippett, sample standard deviation” are shown

Source: adapted from Tol (2008)

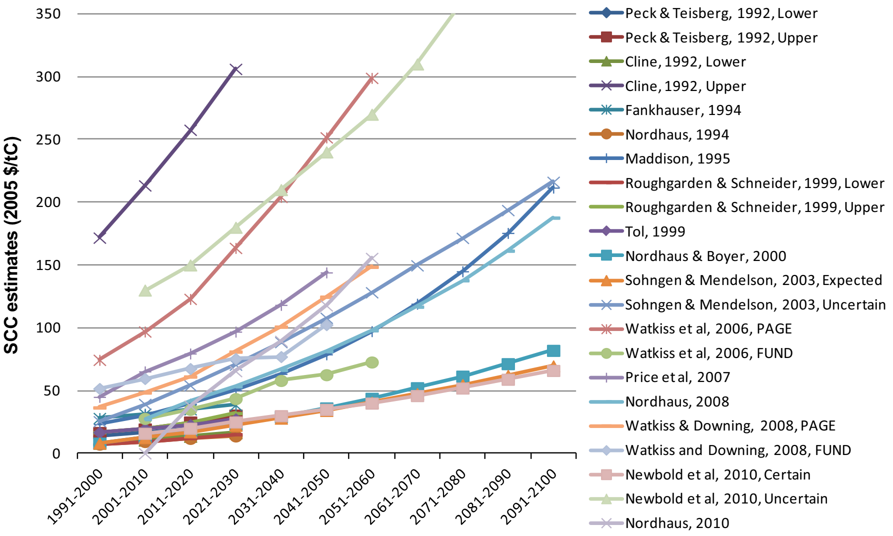

Fig. 4 Time sequences of the SCC estimates ($/tC in 2005). Source: Supplementary material Table A1

meaningless within a cost-effectiveness approach as there is no explicit modeling for damages.

A number of studies have calculated the MAC since the 1990 s. However, unlike the SCC, it has not been the primary objective of the paper except Kuik et al. (2009). In fact, the MAC estimates have been reviewed as an adjunct in the SCC studies, such as that of Watkiss et al. (2006). This is primarily because the MAC largely depends on the stabilization target, which is arbitrarily decided for policy goals; simply put, the more stringent is the abatement goal, the larger is the MAC.

Because Kuik et al. (2009) provides a comprehensive review of the MAC, the study focuses on two important model-comparison projects of Weyant et al. (2006)

Table 2 Parameters of the base case and changed values for sensitivity analysis

Parameter	Description	Base	Changed
ρ	Pure rate of time preference (per year)	0.015	0.001
α	Elasticity of marginal utility of consumption	2.0	1.0
δ_K	Rate of depreciation of capital (per year)	0.10	0.05
$g_{POP}(2005)$	Growth rate of population in 2005 (per decade)	0.35	0.50
$POP_{(\infty)}$	Asymptotic population (millions)	8600	10492
$g_A(2005)$	Initial growth rate of technology (per decade)	0.092	0.132
δ_A	Decline rate of technological change (per decade)	0.001	0.01
PBACK	Cost of backstop technology in 2005 (thousand $/tC)	1.17	2.1
BACKRAT	Ratio between initial and final backstop cost	2	5
g_{BACK}	Cost decline rate of backstop cost (per decade)	0.05	0.02
$\sigma(2005)$	Ratio of uncontrolled emissions to output in 2005	0.13418	0.1
$g_\sigma(2005)$	Growth rate of σ in 2005 (per decade)	−0.073	−0.11
δ_σ	Decline rate of σ (per decade)	0.003	0.0
θ_2	Exponent of abatement cost function	2.8	2.0
ψ_2	Coefficient of damage function	0.0028388	0.00408
ψ_3	Exponent of damage function	2.0	2.5
$M_{AT}(2000)$	Atmospheric CO_2 concentration in 2000 (GtC)	808.9	900
$T_{AT}(2000)$	Atmospheric temperature in 2000 (increase from 1900)	0.7307	1.0
$T_{LO}(2000)$	Lower ocean temperature in 2000 (increase from 1900)	0.0068	0.01
$F_{EX0}(2000)$	Exogenous radiative forcing (non-CO_2) in 2000	−0.06	0.0
ϕ_{12}	Transfer coefficient in carbon cycle	0.189	0.12
ξ_1	Temperature adjustment coefficient for atmosphere	0.22	0.326
ξ_3	Heat loss coefficient from atmosphere to lower oceans	0.3	0.2
$T_{2\times CO2}$	Equilibrium temperature impact of CO_2 doubling	3.0	4.11

See Nordhaus (2008) for the variables and model equations

(EMF-21) and Fawcett et al. (2009) (EMF-22). EMF-21 makes a comparative set of analyses of the economic and energy sector impacts of multi-gas mitigation of greenhouse gases using 18 different models. EMF-22 compares six models for a set of US transition scenarios designed to bracket a range of potential US climate policy goals. In addition to EMF-21 and EMF-22, the MAC estimates in the US Climate Change Science Program (USCCSP) (Clarke et al. 2007) are also reviewed.

Figure 5 summarizes the MAC estimates of the “CO_2 only scenario” in EMF-21, and Fig. 6 summarizes the MAC estimates in 650 and 550 parts per million (ppm) stabilization scenarios in EMF-22. Although EMF-21 sets a unified stabilization target of 650 ppm, Fig. 5 demonstrates a variety of time sequences. The MAC estimates in Fig. 6, especially those for a 650 ppm stabilization target, diverge less compared to the MAC estimates in Fig. 5; however, the estimated range of the MAC is still wide especially in the later period. Unlike the SCC, in which the price

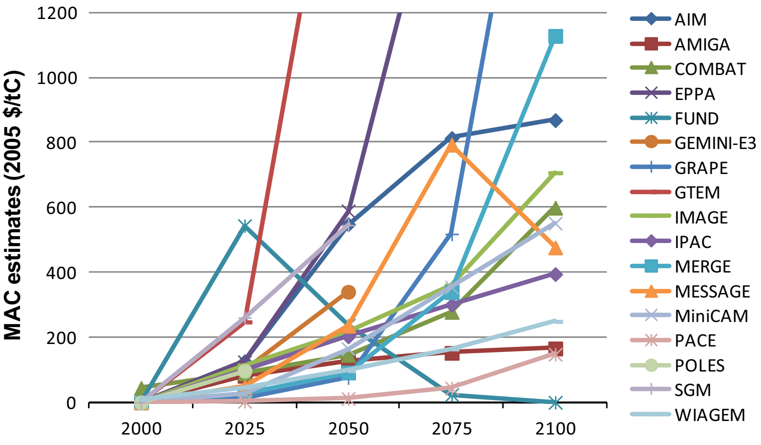

Fig. 5 MAC estimates in EMF-21, CO_2 only scenario (650 ppm stabilization) ($/tC in 2005). Source: Weyant et al. (2006)

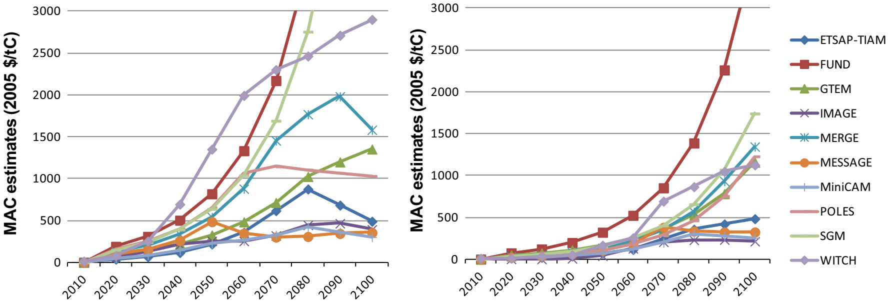

Fig. 6 MAC estimates in EMF-22: (*left*) 550 ppm stabilization (*right*) 650 ppm Stabilization ($/tC in 2005). Source: Fawcett et al. (2009)

increases over time, some of the MAC estimates have a period of a decreasing carbon price.

The scatter plots between the emission reduction and the MAC, using the data for EMF-21 and EMF-22 (see Figs. A1 and A2 and Tables A1 and A2 of the supplementary material) in which the scatter plots are drawn in each period for 2025–2030, 2050, 2075–80, and 2100. There is a noticeable correlation between the emission reduction and the MAC estimated for 2025–2030, showing a gradual reduction in estimated correlation with time. In EMF-22, the slopes of carbon prices per emission reduction become steeper as time progresses both in the 500 ppm and 650 ppm stabilization scenarios, while we cannot see such a tendency in EMF-21.

2.3 Comparison of the SCC and MAC

Nordhaus (2008) makes a comprehensive comparison between the SCC and MAC by time sequence. Figure 7 shows the time sequences calculated by Nordhaus (2008) for the SCC and MAC with different policy targets. In the figure, four types of policy goals are set up: standard discounting, Stern review's discounting for optimal policy with the SCC, stabilizing CO_2 concentration, and stabilizing the temperature increase for cost-effectiveness policies for the MAC. If we use the standard discounting for most policy targets, the SCC is lower than the MAC. However, if we use the Stern Review's discounting, which sets pure time preference rate roughly at zero, the SCC is higher than the MAC with most policy targets.

Figure 8 compares the SCC in Table A1 of the supplementary material with the MAC in Table A2. The figure indicates the MAC with the 650 ppm stabilization scenario, shown as open circles. In general, in 1991–2000, the MAC estimates are lower than the SCC estimates. However, in the later periods, the MAC estimates are much higher in most calculations. This is because the SCC increases constantly, while the time profile of the MAC is shown by an S-shaped curve or an exponential curve. This S-shape or exponential curve of the MAC comes from the implicit damage function characteristics incorporated in the cost-effectiveness analysis. On reaching 100 % emission control, the MAC decreases with the rate of technical progress in the backstop technology.

3 Sensitivity of the SCC

This section provides an SCC sensitivity analysis using the DICE model proposed by Nordhaus (2008). In the sensitivity analysis, we intend to find the parameters that increase the SCC, and the mechanisms of SCC increase by looking at the MB and MC curves of emission reduction.

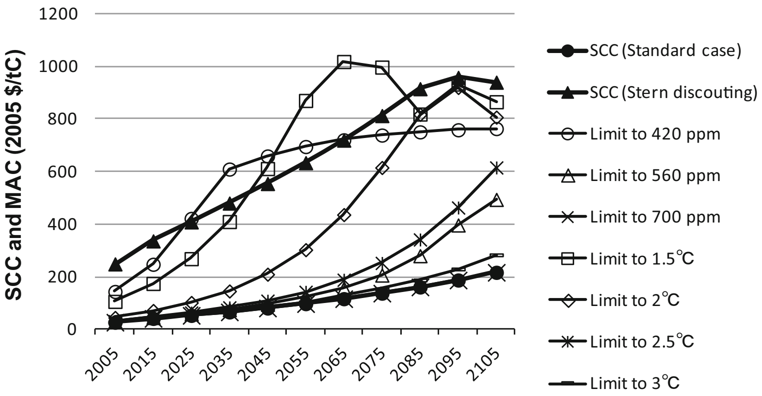

Fig. 7 Time sequence of the SCC and MAC ($/tC in 2005). Policy goals with concentration and temperature limits denote the MAC. Source: Nordhaus (2008)

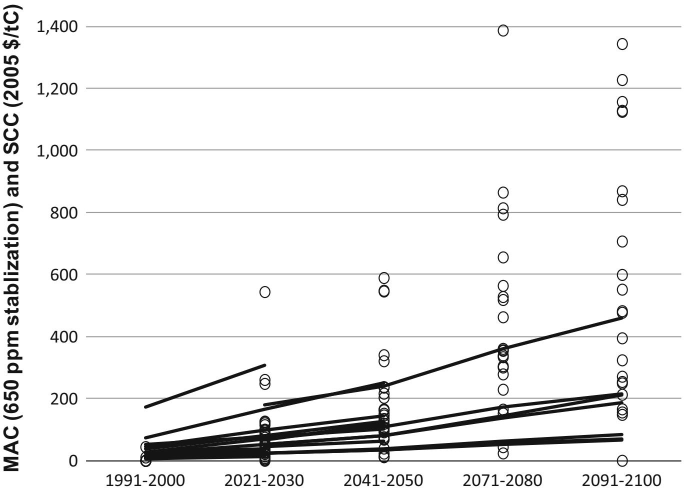

Fig. 8 Summary of the MAC (650 ppm stabilization) and SCC in this section ($/tC in 2005). *Open circles* the MAC, *solid lines* the SCC. Source: Tables A1 and A2

3.1 Method of analysis

Sensitivity analysis is conducted in the following steps:

1. Set up the “Base” case in the DICE model to calculate the SCC
2. Calculate the SCC using the changing parameters (sensitivity analysis)
3. Identify the direction of the parameter that increases the SCC from that shown in the Base case
4. Draw the MB and MC curves, observe the mechanisms that cause the SCC increase (e.g., the upward shift of the MB curve increases the SCC)

DICE is a well-known model in the economic analyses of climate change. The model links the factors that affect economic growth, CO_2 emissions, carbon cycle, climate change, climatic damages, and climate change policies. The version of the DICE model used in this paper is explained in Nordhaus (2008). In the “Base” case, the default parameter set in Nordhaus (2008) is used without modification. The SCC is calculated using the method shown in Nordhaus (1994), which utilizes the dual variables of GAMS output. We also calculate the values for the MC curves by using the method proposed by Nordhaus (1994). Meanwhile, using a climate damage function, the MB from reducing additional ton of carbon emissions is computed; this method is used in Pizer (2002) and Hope (2008). Because the intersection of the MB and MC curves provides the SCC values, mechanisms that cause the SCC increase can be analyzed by observing the changes in the MB–MC curves in the sensitivity analysis.

3.2 Calculation conditions

The CONPOT2 solver in the GAMS modeling system is used in computations. The simulations are shown in 10-year increments from 2005 to 2605. It is convenient to begin the simulation from 2005 because US$ in 2005 are used as the unit in the study's review of the SCC in Sect. 2. To obtain the SCC values, the DICE is run using the cost–benefit approach, maximizing the total net benefit that results from avoiding climate damage. In Nordhaus (2008), this calculation is called the "optimal" run. As explained above, the Nordhaus (1994) method is used for calculating the SCC value.

To obtain the values for the MB and MC curves, the DICE is computed using the cost-effectiveness approach. In estimating the 2005 values for the MB, carbon emissions for that year are reduced by 0.025 Giga tons of carbon (GtC) steps from the Business as usual case, keeping emissions levels in the other period unchanged, and maximizing the total discounted utility in each step of emission reduction. While estimating the 2105 values for the MB, carbon emissions are reduced by 1 GtC step. In calculating the MC values, the CO_2 stabilization target is set at 750, 700, 650, 600, 550, 500, and 450 ppm, maximizing the total discounted utility in each stabilization target.

Table 2 summarizes the parameter settings of the "Base" case and the "Changed" case in the sensitivity analysis. In deciding the parameter values of the changed case, we refer to the parameter ranges shown in Nordhaus (1994, 2007). For ranges of parameter values that are difficult to find, we set the changed values by making rough judgments, similar to Nordhaus (1994). As an example of rough judgment, the parameter value for the *BACKRAT* (the ratio between the initial and final backstop cost) in the "Changed" case is 5.0, but this value is merely chosen because (a) this change shifts the MC curve upward and (b) the change in the parameter is big enough.[4] Such rough judgments are used for $g_{pop}(2005)$, *BACKRAT*, g_{BACK}, $\sigma(2005)$, δ_σ, $M_{AT}(2000)$, $T_{AT}(2000)$, $T_{LO}(2000)$, and $F_{EX0}(2000)$.

We changed the parameter values so that it meets the direction of the increasing carbon price, making the parameter change larger in case of a small price increase and smaller in case of a large price increase.[5] In the sensitivity analysis, the individual parameter is modified to the "Changed" value, keeping other parameters unchanged. Because some parameters do not increase the SCC, we set the following rules for parameter change:

1. The individual parameter is first changed to the direction that causes an upward shift in the MB curve (which results in the SCC increase).
2. If the parameter change does not shift the MB curve upward, we change it to the direction that results in an upward shift in the MC curve.

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[4] The large parameter change is because the *BACKRAT* does not significantly increase the SCC, as explained below.

[5] Nordhaus (1994, 2007) estimates the subjective probability of the parameters. Strictly following Nordhaus' estimates, however, it is difficult to ascertain whether the SCC does not significantly increase because the change in the parameter value is small or because this parameter does not inherently increase the SCC. This is why such adjustments have been made to the parameters.

Table 3 Sensitivity of the SCC ($/tC in 2005)

Changed Parameters	SCC in 2005	SCC in 2055	SCC in 2105
(Base case)	(27.245)	(97.060)	(212.551)
ρ	60.640[b]	208.401[b]	443.768[b]
α	60.595[b]	189.169[b]	388.588[b]
δ_K	24.895	106.022	235.187[a]
$g_{\mathrm{POP}}(2005)$	27.548	98.345	213.356
$\mathrm{POP}_{(\infty)}$	31.098[a]	117.451[a]	258.129[a]
$g_{\mathrm{A}}(2005)$	21.931	101.885	297.210[b]
δ_{A}	32.119[a]	118.183[a]	217.678
PBACK	27.509	97.891	212.095
BACKRAT	27.284	97.256	212.683
g_{BACK}	27.281	97.240	212.664
$\sigma(2005)$	26.009	93.422	209.350
$g_\sigma(2005)$	26.870	95.590	211.292
δ_σ	27.171	96.684	212.289
θ_2	27.886	98.674	210.815
ψ_2	38.822[b]	137.068[b]	298.142[b]
ψ_3	42.510[b]	175.583[b]	409.360[b]
$M_{\mathrm{AT}}(2000)$	27.943	98.560	213.339
$T_{\mathrm{AT}}(2000)$	28.621	97.638	212.896
$T_{LO}(2000)$	27.252	97.077	212.574
$F_{\mathrm{EX0}}(2000)$	27.565	97.750	214.392
$y\phi_{12}$	32.262[a]	110.235[a]	237.059[a]
ξ_1	33.724[a]	119.388[a]	257.143[a]
ξ_3	29.182	104.232	227.720
$T_{2\times\mathrm{CO2}}$	36.491[a]	132.790[b]	294.964[b]

[a,b] 10 and 30 % increase in the SCC, respectively

It should be noted that the parameters not shown in Table 2 are unchanged from Nordhaus' (2008) default parameter settings.

3.3 Results: sensitivity of the social cost of carbon

Table 3 shows the values for the SCC when the parameters are changed individually. Six parameters increase the SCC from the base case by more than 30 %, and five others increase it by more than 10 %.[6] Four of five parameters that increase the SCC by more than 30 % are related to climate damage. Note that the pure rate of time preference (ρ) and the elasticity of marginal utility of consumption (α) are parameters that distribute climate damage over time, even though they both appear to be merely macroeconomic parameters at first glance. The parameters that

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[6] Note that the SCC's increase depends on the degree the of parameter change. In this study, we made the parameter change bigger if the price increase is small and vice versa. The sensitivity analysis of Nordhaus (1994) gives a slightly different result because of this adjustment.

have a particularly significant influence are ρ, α, and Ψ_3, which are exponents of the damage function.[7] It should be noted that the third parameter, has an especially significant influence.[8] Therefore, the low discount rate in the Stern Review or other studies is merely one among several causes of high SCC; we also need to focus on other parameters, such as Ψ_3. Meanwhile, a quantitative comparison of influence of the parameter values ρ, α, and Ψ_3 is difficult; consequently, the influence of the values of parameter change should be interpreted as qualitative measures.

Figure 9 shows the sensitivity of the SCC by time trends; each computation uses parameters that are different from those discussed above. The SCC range was 27 \$/tC (base case) to 61 \$/tC in 2005, and is estimated to increase to 213–444 \$/tC in 2105. The figure also shows the SCC increasing at a roughly constant rate over time.

3.4 Results: sensitivity of the MB–MC curves

We analyzed the sensitivity of the above SCC. We focus on the mechanisms of the SCC increase by observing the sensitivity of the MB–MC curves (note that detailed figures are shown in Fig. A4 in the supplementary material). To summarize the influence of the parameters and discuss the mechanisms associated with the increase in the SCC, Table 4 classifies the parameters for the sensitivity analysis into three groups. There are two parameter groups in which the SCC increases; Group 1 parameters comprise ρ, α, Ψ_2, Ψ_3, ϕ_{12}, ξ_1, and T_{2XCO2}, and Group 2 parameters comprise δ_K, POP(∞) and g_A (2005). Among Group 1 parameters, the MC curve does not change; only the upward shift of the MB curve contributes to the SCC increase. On the other hand, among Group 2 parameters, both the MB and MC curves shift in the process of the SCC increase; the MC curve shifts downward, but the upward shift of the MB curve compensates for the downward shift of MC curve, resulting in the SCC increase; Group 2 parameters shift the MB curve upward by increasing GDP and CO_2 emissions, but the increase in GDP reduces the emission/GDP ratio, shifting the MC curve downward.

Group 3 parameters, δ_A, PBACK, BACKRAT, g_{BACK}, σ(2005), g_σ(2005), δ_σ, and θ_2, do not increase the SCC while shifting the MC curve upward, because of our parameter change rule. Since the MB curve is horizontal in CO_2 emission reduction under the given damage function,[9] a single MC curve shift does not contribute to the SCC increase, which is different from that shown in Fig. 1. In the rest of the parameters, which do not belong to the three above groups, there is no shift in the MB and MC curves. It should be noted that the sensitivity analysis discussed above

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[7] The damage function $\Omega(t)$ takes the form of $\Omega(t) = \{1 + \Psi_2 T_{AT}(t)^{\Psi 3}\}^{-1}$, where $T_{AT}(t)$ is the atmospheric temperature.

[8] In Table 3, Ψ_3 has a smaller influence than ρ; this is because we made the parameter change smaller. $\Psi_3 = 3.0$ or 4.0 produces a big increase in the SCC.

[9] Pizer (2002) discusses why the MB curve is relatively flat in climate damage mitigation. Pizer highlights that 1) climate damage is presumed to be a gradual phenomenon with little consequence from small temperature changes, and 2) damage depends on the accumulated stock of greenhouse gases (GHGs) in the atmosphere and not the annual flow. Consequently, unless abrupt and catastrophic damages are assumed, the MB curve is roughly horizontal. In fact, $\Psi_3 = 4.0$ still produces a horizontal MB curve.

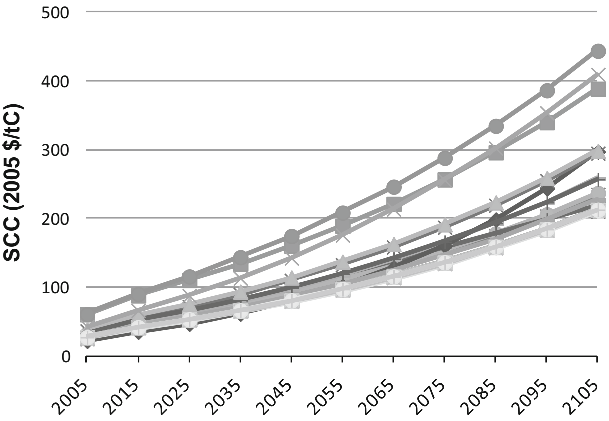

Fig. 9 Sensitivity of the SCC by time trend ($/tC in 2005). Different parameters are used in each computation

is a rather qualitative one, even though the increase in the SCC is quantified (Rise^b and Rise^a).

4 Sensitivity of the MAC with a 500 ppm stabilization target

In this section, we provide a sensitivity analysis of the MAC when the stabilization target is 500 ppm. In the sensitivity analysis, we apply the same parameter changes as for the SCC sensitivity analysis in the previous section. The sensitivity analysis in this section focuses on comparing the mechanisms in the increase in the SCC and MAC.

4.1 Calculation conditions

The sensitivity analysis in this section is the same as that in the previous section, except that the MAC is the target of the analysis. As a result, we follow the same sensitivity analysis procedure as in the previous section:

1. Set the "Base" case in the DICE model, and calculate the MAC with a 500 ppm stabilization target
2. Calculate the MAC with changing parameters (sensitivity analysis)
3. Draw the MC curves by observing the mechanisms for the MAC increase (e.g., the upward shift of the MC curve increases the MAC)

The calculation condition for the simulations in this section is the same as that in the previous section except for the use of the CO_2 stabilization target. We set the stabilization target at 500 ppm considering the recommendation of the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (IPCC

Table 4 Summary of the sensitivity analyses on the SCC

Changed parameters	Parameter group	SCC	MB curve	MC curve
ρ	Group 1	Rise[b]	Up	
α	Group 1	Rise[b]	Up	
δ_K	Group 2	Rise[a]	Up	Down
$g_{POP}(2005)$				
$\mathrm{POP}_{(\infty)}$	Group 2	Rise[a]	Up	Down
$g_A(2005)$	Group 2	Rise[b]	Up	Down
δ_A	Group 3[c]	Rise[a]	Up	Up
PBACK	Group 3			Up
BACKRAT	Group 3			Up
g_{BACK}	Group 3			Up
$\sigma(2005)$	Group 3			Up
$g_\sigma(2005)$	Group 3			Up
δ_σ	Group 3			Up
θ_2	Group 3			Up
ψ_2	Group 1	Rise[b]	Up	
ψ_3	Group 1	Rise[b]	Up	
$M_{\mathrm{AT}}(2000)$				
$T_{\mathrm{AT}}(2000)$				
$T_{\mathrm{LO}}(2000)$				
$F_{\mathrm{EX0}}(2000)$				
ϕ_{12}	Group 1	Rise[a]	Up	
ξ_1	Group 1	Rise[a]	Up	
ξ_3				
$T_{2\times\mathrm{CO2}}$	Group 1	Rise[b]	Up	

[a,b] 10 and 30 % increase in the SCC, respectively

[c] δ_A increases the SCC in 2005 and 2055, but not in 2105, while shifting the MC curve upward. Thus, we classify δ_A as a Group 3 parameter

2007),[10] and run the DICE model according to the cost-effectiveness approach, thus, maximizing the total discounted utility with this stabilization target. The MAC is estimated by using the method proposed by Nordhaus (1994), using dual variables of the GAMS output. In the MAC calculation, the stabilization target is set at 500 ppm, as mentioned above, but in the calculation for the MC curve, it is reduced by 20 ppm steps from 750 to 450 ppm. The parameters in the "Base" case and "Changed" case in the sensitivity analysis are the same as those shown in Table 2 in the previous section. We use the same parameters between the analyses of the SCC and the MAC to compare the mechanisms of the increase in the SCC and the MAC.

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[10] While there are emission stabilization, concentration stabilization, and temperature stabilization, this study uses concentration stabilization since it is the most common.

For the sensitivity analysis, the individual parameter is modified to the “Changed” value, keeping the other parameters unchanged.

4.2 Results: sensitivity of the MAC

Table 5 shows the MAC responses with a 500 ppm stabilization target when the parameters are changed individually. Nine parameters increase the MAC by more than 30 % from the base case, and two other parameters by more than 10 %. Six of them ρ, α, δ_K, POP(∞), g_A(2005), and ϕ_{12} increase both the SCC in Sect. 3 and the MAC presented in this section; these parameters increase the SCC and the MAC by shifting the MB curve upward and increasing the amount of emission reduction, respectively.

There are parameters that exclusively increase either the SCC or the MAC. The parameters that increase the SCC but not the MAC are δ_A, Ψ_2, Ψ_3, ξ_1, and T_{2XCO2}; since Ψ_2, Ψ_3, ξ_1, and T_{2XCO2} are parameters directly related to climate damage. When the stabilization target is given exogenously, such parameters lose their influence on the carbon price. The parameters that do not increase the SCC but increase the MAC include PBACK, BACKRAT, g_{BACK}, and θ_2, which are abatement cost parameters, and M_{AT}(2000), which determines the level of emission reduction. Concerning the period during which parameters have an influence on the SCC and MAC in the early period of 2005 (and 2055), the parameters that distribute climate damage and increase the MAC are ρ and α. Abatement cost parameters *PBACK*, *BACKRAT*, g_{BACK}, *and* θ_2 have had influences after the mid-21st century.

Figure 10 indicates the MAC sensitivity with a 500 ppm stabilization target by time trends; each computation uses different parameters in the same manner as above. The range for the MAC is 7–40 $/tC in 2005, increasing to 518–1070 $/tC in 2105. The MAC in 2005 is lower than the SCC of Sect. 3, which ranges from 27 to 61 $/tC; however, the MAC is estimated to be higher than the SCC in 2015, which ranges from 213 to 444 $/tC.

Figure 11 shows the MAC for the base case with different stabilization targets. When the stabilization target is less than 600 ppm, the MAC’s time trend takes an S-shaped pattern. In the early years, the MAC is low; it increases with the increasing slope and gradually stabilizes. It should be noted that the time trend for the SCC shows it as increasing at roughly a constant rate over time.

4.3 Results: sensitivity of the MC curve and the MAC

We now turn to the mechanisms that result in the MAC increase with a 500 ppm stabilization target. Note that Fig. A5 of the supplementary material shows the responses of the MC curve and the MAC with a 500 ppm stabilization target when the parameter values are individually changed.

Table 6 summarizes sensitivity analysis of this section, classifying the parameters into four groups. There are three parameter groups in which the MAC with a 500 ppm stabilization target increases: Group A parameters of ρ, α, M_{AT}(2000), and ϕ_{12}; Group B parameters of δ_K, POP(∞), and g_A(2005); and Group C parameters of *PBACK*, *BACKRAT*, g_{BACK}, and θ_2. For Group A parameters, the MC curve itself

Table 5 Sensitivity of the MAC with a 500 ppm stabilization target ($/tC in 2005)

Changed parameters	MAC in 2005	MAC in 2055	MAC in 2105
(Base case)	(17.853)	(256.266)	(627.929)
ρ	38.278[b]	294.798[a]	647.988
α	40.407[b]	296.014[a]	646.369
δ_{K}	18.303	335.274[b]	657.517
$g_{POP}(2005)$	18.752	276.541	630.492
$POP_{(\infty)}$	25.099[b]	395.651[b]	680.427
$g_{A}(2005)$	17.307	453.611[b]	753.879[a]
δ_{A}	19.837	226.106	517.782
PBACK	30.776[b]	436.331[b]	1070.103[b]
BACKRAT	19.310	274.854	719.513[a]
g_{BACK}	19.221	273.874	710.244[a]
$\sigma(2005)$	6.941	88.335	518.211
$g_{\sigma}(2005)$	12.628	177.330	534.103
δ_{σ}	16.911	242.913	597.940
θ_{2}	37.530[b]	580.658[b]	752.604[a]
ψ_{2}	17.853	256.266	627.929
ψ_{3}	17.853	256.266	627.929
$M_{AT}(2000)$	25.928[b]	400.067[b]	641.544
$T_{AT}(2000)$	17.853	256.266	627.929
$T_{LO}(2000)$	17.853	256.266	627.929
$F_{EX0}(2000)$	17.853	256.266	627.929
ϕ_{12}	37.061[b]	499.819[b]	696.591[a]
ξ_{1}	17.853	256.266	627.929
ξ_{3}	17.853	256.266	627.929
$T_{2\times CO2}$	17.853	256.266	627.929

[a,b] 10 and 30 % increase in the MAC, respectively

does not change; the MAC with a 500 ppm stabilization target increases along the MC curve by the amount of increase in emission reduction. For Group B parameters, the MC curve shifts downward, but the MAC with a 500 ppm stabilization target increases by the amount of increase in emission reduction, similarly to the Group 2 parameters of the SCC in Sect. 3. For Group C parameters, the MC curve shifts upward and the MAC with a 500 ppm stabilization target increases; this is similar to Group 3 parameters for the SCC in terms the upward shift of the MC curve, but the upward shift increases the MAC in the Group C parameters while it does not increase the SCC in the Group 3 parameters.

The rest of the parameters, which do not belong to the above three groups, do not increase the MAC with a 500 ppm stabilization target. In Group D parameters of δ_{A}, $\sigma(2005)$, $g_{\sigma}(2005)$, and δ_{σ}, the MC curve shifts upward similar to the Group C parameters, but the MAC with a 500 ppm stabilization target decreases.[11] The most

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[11] The MAC increases if we change the Group D parameters in the opposite direction. In this sense, Group D parameters are similar to Group B parameters in the sensitivity of the MAC.

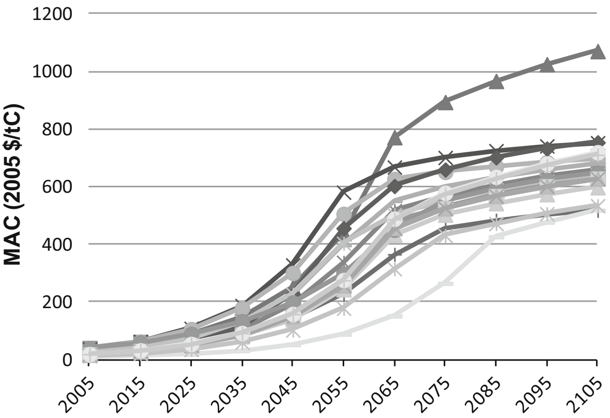

Fig. 10 Sensitivity of MAC by time trend, stabilizing at 500 ppm (2005 $/tC). Note: Different parameters are used in each computation

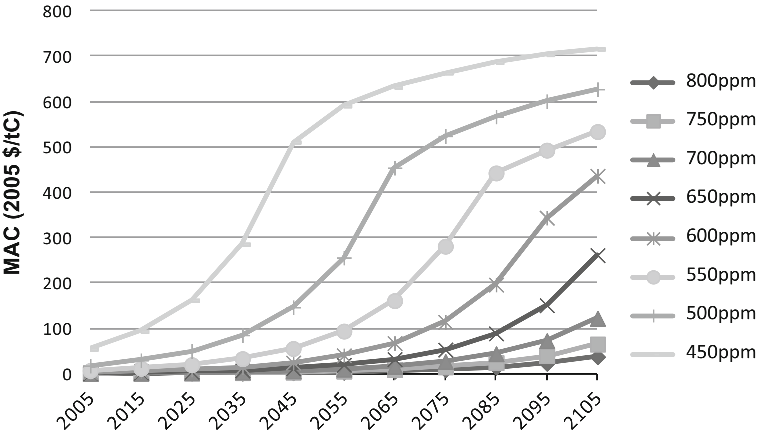

Fig. 11 The MAC (Base case) with different stabilization targets ($/tC in 2005). Legends indicate stabilization targets

noticeable difference between the sensitivity of the SCC and MAC is that no parameters shift the MC curve upward and increase the SCC at the same time, while the Group C parameters shift the MC curve upward and increase the MAC.

5 Discussion and conclusions

This study uses the DICE model proposed by Nordhaus (2008) to examine the mechanisms in which the individual parameters increase the SCC and MAC. This study's findings contribute to the discussions on the choice of the SCC or MAC for

Table 6 Summary of the sensitivity analyses on the MAC

Changed parameter	Parameter group	MAC (500 ppm Limit)	MC Curve
ρ	Group A	Rise[b]	
α	Group A	Rise[b]	
δ_K	Group B	Rise[b]	Down
$g_{\mathrm{POP}}(2005)$			
$\mathrm{POP}_{(\infty)}$	Group B	Rise[b]	Down
$g_{\mathrm{A}}(2005)$	Group B	Rise[b]	Down
δ_{A}	Group D		Up
PBACK	Group C	Rise[b]	Up
BACKRAT	Group C	Rise[a]	Up
g_{BACK}	Group C	Rise[a]	Up
$\sigma(2005)$	Group D		Up
$g_{\sigma}(2005)$	Group D		Up
δ_{σ}	Group D		Up
θ_2	Group C	Rise[b]	Up
ψ_2			
ψ_3			
$M_{\mathrm{AT}}(2000)$	Group A	Rise[b]	
$T_{\mathrm{AT}}(2000)$			
$T_{\mathrm{LO}}(2000)$			
$F_{\mathrm{EX0}}(2000)$			
ϕ_{12}	Group A	Rise[b]	
ξ_1			
ξ_3			
$T_{2\times\mathrm{CO2}}$			

[a,b] 10 and 30 % increase in the MAC, respectively

policy cost–benefit analyses, the setting of carbon taxes, and the establishment of long-term CO_2 stabilization targets.

First, the discount rate (ρ) was found to not be the only factor that significantly increases the carbon price. Second, by analyzing the MB and MC curves, two patterns (mechanisms) of increase in the SCC, and three patterns (mechanisms) of increase in the MAC were observed. Third, the difference between the SCC–MAC increases is primarily caused by the horizontal MB curve in CO_2 emission reduction; an upward shift of the MC curve increases the MAC but never increases the SCC. Another contribution of this study is its use of figures (Figs. 12, 13) to show these results and make them easily understood.

Table 7 summarizes the sensitivity analyses on the SCC, the MAC, and the MB–MC curves shown in Sects. 3 and 4. Meanwhile, Fig. 12 schematically explains the increase in the SCC in response to the MB–MC curve shifts, and Fig. 13 schematically explains these shifts and the consequent increase in the increase in the

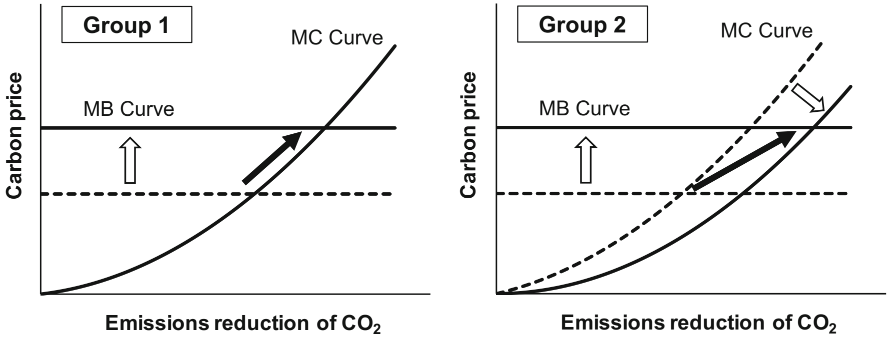

Fig. 12 Schematic explanations of the increase in the SCC from the change of parameters

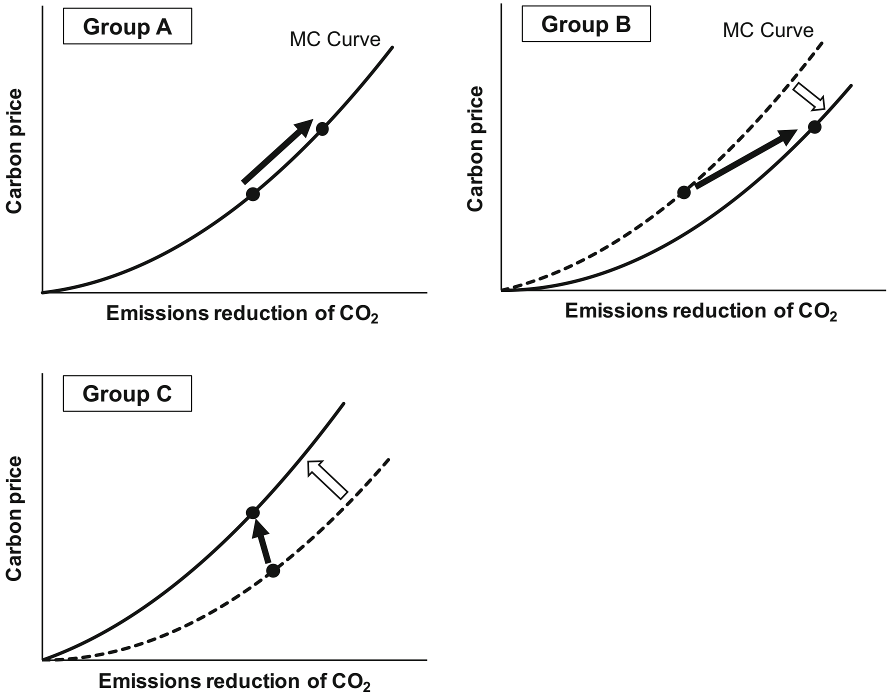

Fig. 13 Schematic explanations of the increase in the MAC from the change of parameters

MAC. These results apply to various policy discussions. For example, the change of the *PBACK* (the cost of back stop technology in 2005) does not affect the SCC but significantly increases the MAC; consequently, the choice of the SCC or MAC affects the carbon tax when the cost of backstop technology has a range.

The importance of these findings indicates the potential for further research into the mechanisms of carbon price increases. First, the MB–MC analysis in this study

Table 7 Summary of the sensitivity analyses in this study

Changed parameter	Parameter group	SCC	MAC 500 ppm	MB curve	MC curve
ρ	1 and A	Rise[b]	Rise[b]	Up	
α	1 and A	Rise[b]	Rise[b]	Up	
δ_K	2 and B	Rise[a]	Rise[b]	Up	Down
$g_{\mathrm{POP}}(2005)$					
$\mathrm{POP}_{(\infty)}$	2 and B	Rise[a]	Rise[b]	Up	Down
$g_{\mathrm{A}}(2005)$	2 and B	Rise[b]	Rise[b]	Up	Down
δ_{A}	3 and D	Rise[a]		Up	Up
PBACK	3 and C		Rise[b]		Up
BACKRAT	3 and C		Rise[a]		Up
g_{BACK}	3 and C		Rise[a]		Up
$\sigma(2005)$	3 and D				Up
$g_{\sigma}(2005)$	3 and D				Up
δ_{σ}	3 and D				Up
θ_2	3 and C		Rise[b]		Up
ψ_2	1	Rise[b]		Up	
ψ_3	1	Rise[b]		Up	
$M_{\mathrm{AT}}(2000)$	A		Rise[b]		
$T_{\mathrm{AT}}(2000)$					
$T_{\mathrm{LO}}(2000)$					
$F_{\mathrm{EX0}}(2000)$					
ϕ_{12}	1 and A	Rise[a]	Rise[b]	Up	
ξ_1	1	Rise[a]		Up	
ξ_3					
$T_{2\times\mathrm{CO2}}$	1	Rise[b]		Up	

[a,b] 10 and 30 % increase in the carbon price, respectively

is a static analysis, while CO_2 emission reductions are necessarily dynamic. Therefore, a dynamic analysis into the understanding of CO_2 abatement policy is required. Second, an analytical study to further disentangle the mechanisms of carbon price increase is also required. In particular, it is important to understand the mechanism of MAC change and the S-shaped time profile, because analyzing only the MC curve and the MAC has limitations. For example, when analyzing the MAC, the implicit damage function cannot be visually detected. Third, the mechanisms associated with the increase in the SCC and MAC should be examined from the perspective of policy implications. For example, this study's results suggest that the shift in the MC curve should affect the MAC in a long-term stabilization simulation, but not the SCC in a policy cost-benefit analysis. By incorporating the above points, the analysis of emission reduction will present a more comprehensive understanding of the price of carbon and its policy application.

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