Comput Econ (2019) 53:169–189
https://doi.org/10.1007/s10614-017-9735-z

The Limit of Global Carbon Tax and its Climatic and Economic Effects

Gaoxiang Gu[1] · Zheng Wang[2,3]

Accepted: 30 August 2017 / Published online: 4 September 2017

Abstract Global carbon tax has been widely studied for a long time. However, its economic feasibility in specific countries and sectors has not been taken seriously. This study focuses on the limit of carbon tax in carbon reduction and its economic and climatic impacts. To accurately predict the economic impact of carbon tax for assessing its feasibility, a climatic-economic IAM named CIECIA is applied and improved by adding a carbon tax module. In this model, two levy types of carbon tax with an adjustable revenue distribution mode are designed. On the basis of this, the emission reduction limits of carbon tax and its economic and climatic effects are simulated. The results indicate that carbon tax reduces emissions in two ways: directly, by reducing the output of high-emission sectors, and indirectly, by promoting the adoption of low-carbon technologies. Global carbon tax can achieve the 2 °C climate mitigation target under a national independent mode, whereas under a global uniform mode, the limit of temperature control is around 2.46 °C. As the cost of carbon reduction, the economic loss is also significant, especially in developing countries. Investing R&D by using carbon tax revenue is an effective way to both reduce emissions further and ease economic loss. On the basis of this, we propose a Pareto improving scheme that both ensures the economic benefits of all participating countries and achieves climate mitigation targets.

✉ Gaoxiang Gu
caesar161@126.com

1 Population Research Institute, East China Normal University, Shanghai 200241, China

2 Institute of Policy and Management, Chinese Academy of Sciences, Beijing 100080, China

3 Key Laboratory of Geographical Information Science, Ministry of State Education of China, East China Normal University, Shanghai 200241, China

Keywords Limiting carbon tax · Integrated assessment model · Tax revenue distribution · R&D investment · Process technology progress · Pareto improvement

1 Introduction

Carbon tax policy has been generally considered as one of the most market effective measures for carbon emission abatement (Baranzini et al. 2000). Compared with other mitigation measures, carbon tax has several advantages, e.g., bringing financial and environmental *double welfares*, promoting the production cost decrease of firms, and stimulating the adoption of energy-saving technologies, and it can be adjusted in time if necessary (Pearce 1991). Compared with other reduction measures, e.g., carbon emission caps, emission permit trading, and emission subsidies, carbon tax can run in lower quality systems and achieve better effects (Brandt and Svendsen 2014; Avi-Yonah and Uhlmann 2009). Therefore, as a climate governance measure, it has obtained long-term and wide support (Zhang and Baranzini 2004).

According to Wang et al. (2016), two principles, i.e., climatic effectiveness and economic feasibility, should be considered in the study of carbon governance. The effectiveness means that the carbon reduction measure should realise the global climate mitigation targets. The climatic effectiveness of carbon tax has been widely discussed through scenario simulations, and many studies have proven that it is possible to rely on global carbon tax alone to achieve climate mitigation targets. However, those studies took insufficient account of its economic effects on countries, in lowering the economic feasibility of their carbon tax schemes.

A climate policy is feasible if it can be accepted by all the reduction participants (Wang et al. 2016). Implementation of carbon tax will affect the economy of countries and may lead to international economic imbalance. The economic impact is a major concern in climate mitigation cooperation and has become a primary reason for divergences in global negotiations (IPCC 2014). Moreover, the economic impact also reflects fairness, because the share of economic loss caused by reductions can be regarded as a manifestation of *Common but Differentiated Responsibilities*. Thus, balancing economic losses among countries and controlling them within an acceptable range are crucial for the economic feasibility of carbon tax.

From the aspect of modelling, a detailed multi-national-sectoral economic model that accurately predicts the economic impacts is necessary to assess the economic feasibility of carbon tax. Unfortunately, few studies have done this. Most of the current IAMs are still rough in the depiction of economic processes. Manne and Richels (2006) researched the global optimal carbon tax rate under the condition of limited radiative forcing by using the MERGE model. This study failed to analyse economic impacts of carbon tax policy at the country level. Nordhaus (2008) studied global carbon tax by using the DICE-2007. DICE model considered the world as a whole and could not study the impacts of carbon tax policy at either a national or sectoral level. Moreover, its technological mechanism was too simple, which also influenced its accuracy. Similar problems also existed in studies by Leimbach et al. (2010) and Elliott et al. (2010). Lemoine and Traeger (2014) improved the DICE model and used it to calculate the optimal carbon tax in a tipping climate, and Cai et al. (2012) introduced dynamic stochastic mechanism into the DICE model and studied the optimal carbon tax in a tipping climate under uncertainty of anthropogenic carbon on economy. However, these works failed to improve the components of economy and technological progress of DICE.

In summary, the main problems with the above IAMs are over-simplification of their economic modules and their technological progress mechanism. Moreover, these studies barely discussed the use of carbon tax revenue. To overcome those shortcomings, this study has adopted and improved an IAM, called the Capital, Industrial Evolution, and Climate Change Integrated Assessment model (CIECIA), to conduct comprehensive research on carbon tax.

CIECIA is a policy simulation climatic-economic IAM (Wang et al. 2016). The whole structure of CIECIA comprises the economic model, the climatic model, and other supplementary modules, following on from and developing the structures of the DICE/RICE model and MRICES model series (Nordhaus and Yang 1996; Nordhaus 2008; Wang et al. 2012a, b). In contrast to those models, the economic core of CIECIA is a multi-country-sector general equilibrium model that is extended, based on Jin (2012), to depict the economic relationships among sectors of countries, and that adopts a stochastic technological shock mode (Lorentz and Savona 2008), driven by knowledge capital, to depict the self-selection mechanism of production technology of specific sectors. In addition, the global carbon cycle model is based on Svirezhev et al. (1999), and the climate damage function follows the RICE model (Nordhaus and Yang 1996).

In this study, based on the standard version, we developed a carbon tax module that includes a revenue distribution mode and imported it into CIECIA. This carbon tax module includes two types of carbon tax, i.e., global uniform and national independent, and the carbon tax revenue will either be invested in the production of low carbon-intensive sectors and R&D or be consumed directly. The global capital flow and investment module was also modified for the import of carbon tax. On the basis of this carbon-tax-integrated version of CIECIA, the limit of global carbon tax under two modes and its economic and climatic impacts are studied, in addition to the use of the revenue, especially in R&D investment. On the basis of these, a Pareto improving scheme is presented, and some global carbon governance measures are suggested.

2 Model and Data Sources

Because of the limitation of space, only the modules that have an important connection to carbon tax and its revenue distribution are introduced in this section. These are the carbon tax module, the technological progress module and the economic core of CIECIA. The details of CIECIA can be seen in Wang et al. (2016). The basic assumptions of CIECIA include the commodity and capital flow among sectors of countries being free, with no trading barrier; the production sectors in individual countries sharing a wage rate and a labor technological level in one step; sectors in different countries having the same fixed capital output elasticity; and all the countries involved having the same discounting rate. In this study, country is denoted by i, sector is denoted by j, and step, i.e., year, is denoted by t henceforth.

2.1 Production Module

A two-layer formation comprising the Leontief function and the Cobb-Douglas function is employed in CIECIA. The sectoral output is composed of value added and intermediate inputs, and the value added is formed by labor, capital stock, and knowledge capital.

$$X_{i,t}^{j} = \min\left\{\frac{M_{1,i,t}^{j}}{a_{1,j,i,t}},\ldots,\frac{M_{k,i,t}^{j}}{a_{k,j,i,t}},\ldots,\frac{M_{I,i,t}^{j}}{a_{I,j,i,t}}, X_{i,j,t}^{*}\right\},\quad k = 1,\ldots,I \tag{1}$$

$$X_{i,j,t}^{*} = \Omega_{i,j,t}\left(K_{i,t}^{j}\right)^{\alpha_i}\left(A_t^{j} L_{i,t}^{j}\right)^{1-\alpha_i}\left(Z_t^{j}\right)^{\beta_{j,t}^{Z}} \tag{2}$$

$$Y_{i,t}^{j} = \sum_{k}^{I} M_{k,i,t}^{j} p_{k,t} + X_{i,t}^{j} p_{i,t} \tag{3}$$

where $X_{i,t}^{j} p_{i,t}$ represents the sectoral value added, $M_{k,i,t}^{j}$ is the intermediate input, $a_{k,j,i,t}$ is the coefficient of intermediate input, $K_{i,t}^{j}$ is the capital stock, $L_{i,t}^{j}$ denotes the labor, A_t^{j} is the labor technology level, α_i is the output elasticity of fixed capital, Z_t^{j} denotes the knowledge stock, $\beta_{j,t}^{Z}$ denotes the output elasticity of knowledge capital, $p_{k,t}$ denotes the price, and $\Omega_{i,j,t}$ is the damage coefficient of climate change.

According to Abel (2003) and Jin (2012), the fixed capital stock also updates in Cobb-Douglas form. The update of the knowledge capital is accumulated with Perpetual Inventory Method.

$$K_{i,t+1}^{j} = a\left(Ik_{i,t}^{j}\right)^{\phi}\left(K_{i,t}^{j}\right)^{1-\phi} \tag{4}$$

$$Z_{t+1}^{j} = (1-\delta_Z)\, Z_t^{j} + Iz_t^{j} \tag{5}$$

where $Ik_{i,t}^{j}$ is the fixed capital investment of sector i in country j, Iz_t^{j} is the R&D investment, ϕ denotes the output elasticity of in capital production, and δ_Z denotes the depreciation rate of knowledge capital.

According to Jin (2012), the associated price index and the equilibrium prices of products are:

$$\bar{p}_t = \prod_{i}^{I}\left(p_{i,t}\right)^{\gamma_i} = 1 \tag{6}$$

$$p_{i,t} = \frac{\gamma_i}{X_{i,t}^{g}} X_t^{g} \tag{7}$$

The Keynes–Ramsey utility is adopted to reflect the change of economic strength during simulation, which is the analyzing basis of the economic impact of carbon tax.

$$UA^j\left(T\right)=\sum_{t=1}^{T}\left(\beta+1\right)^{-t}\,Pop_t^j\,\frac{\left(C_t^j/Pop_t^j\right)^{1-\rho}}{1-\rho} \tag{8}$$

where $UA^j\left(T\right)$ is the cumulative utility of country j until step T, C_t^j denotes the consumption, Pop_t^j denotes the population, and β is the discounting rate and its value is 0.015 according to Wang et al. (2012b); ρ is the time preference of consumer.

2.2 Carbon Tax Module

As the energy uses of different sectors are all supplied by the energy sector, the total industrial energy use in one step can be obtained by aggregating the intermediate energy product inputs.

$$E_{i,t}^j=\tau_{i,j}^E M_{E,i,t}^j \tag{9}$$

where $E_{i,t}^j$ denotes the sectoral energy use, and $\tau_{i,j}^E$ is the ratio of energy use to unitary energy product, i.e. energy intensity. The carbon emissions of country j can be obtained by its energy consumption, energy structure, and carbon emission intensities of fossil energies.

$$QP_t^j=\sum_{e}^{E}\tau_{j,e}^C\kappa_{e,j,t}\left(E_{j,t}^C+\sum\nolimits_i^I E_{i,t}^j\right) \tag{10}$$

where $\kappa_{e,j,t}$ is the consuming share of the energy that is supplied by fossil energy e of country j in step t, $\tau_{j,e}^C$ is the carbon emission intensity of energy e in country j, and $E_{j,t}^C$ is the final consumption of energy. The fossil energy is divided into oil, coal, and natural gas.

There are two main methods of carbon tax levy: on the production side and the consumption side. Levying carbon tax on the production side is easier and more conducive to the governance of carbon tax and the source control of carbon emissions, and it is widely accepted in academia. However, the carbon emissions of unitary energy products are different when they are consumed by different sectors in different countries (Table 1). Thus, it is unfair to levy carbon tax on the production side.

Therefore, in this study the consumption-side levying method is adopted and the levy of carbon tax of a sector can be given by

$$CT_{i,t}^j=\vartheta_t^j\sum\nolimits_e^E E_{i,t}^j\tau_{j,e}^c\kappa_{e,j,t} \tag{11}$$

where ϑ_t^j the tax rate.

In many CGE models, carbon tax is always added into the production cost and transferred to the consumers by increasing product prices. As the price increases, the product demand declines, along with the carbon emissions in the process of production or consumption. The current model adopted a different way to shift the carbon tax to the investments that the sectors gain for the capital stocks. That is, levying carbon tax from the investments made by sectors. The sectoral carbon tax levy is given by

Table 1 Comparisons of sectoral carbon intensities of fossil energies in China and the USA in 2007 ($MtCO_2$/Mtoe). *Data source* GTAP-8

Fossil energy	China				USA			
	Oil industry	Electricity industry	Chemical industry	Heavy industry	Oil industry	Electricity industry	Chemical industry	Heavy industry
Coal	0.0950	3.8205	3.8060	3.8143	/	3.8775	3.8768	3.8806
Oil	/	3.0458	0.6339	5.3736	/	3.0000	0.4737	/
Natural gas	2.1112	2.2341	1.2300	2.2334	0.4463	2.2274	1.7724	2.2313
Petro	0.3149	2.8734	0.8082	2.6689	1.4424	1.3171	0.2581	2.8933

"/" means the consumption or carbon emission of this type of fossil is 0

$$I_{i,j,t}^{c-tax-out} = \phi CT_{i,t}^{j} \tag{12}$$

where $I_{i,j,t}^{c-tax-out}$ is the tax loss of the investment of sector i in country j.

For ensuring economic stability, it is assumed that carbon tax should not exceed its sectoral investment. This means that the carbon tax reaches its limit when it equals the investment made by the sector.

$$CT_{i,j,t}^{\lim} = Ik_{i,t}^{j}/\phi \tag{13}$$

Under the levy mode of most CGE models, as the carbon tax increases to a very high level, the demand for high-emission products declines significantly, leading to excess capacity in the high-emission sectors and creating idle capital and unemployed labourers. In CIECIA, as the carbon tax is limited to the range of sectoral investment, the scales of production of all the sectors in countries are stabilised to avoid large economic fluctuation. As the world has been experiencing on-going economic recession since 2008, a carbon reduction policy that might lead to a global economic crash is obviously unacceptable. Thus, the meaning of limiting carbon tax in CIECIA can be explained from the perspective of the tax levy mode of a CGE model, though adopting a different levy method.

From the aspect of global investment, carbon tax affects the capital return rates of sectors and, thus, exerts significant influence on international capital flow. The investment mode of CIECIA is composed of an investment return rate equilibrium mode and a capital attractiveness mode. Under the influence of carbon tax, the function is changed into:

$$R_1\left(i,j,t\right) = \frac{\alpha_i \gamma_i \mathrm{E}\left[\frac{X_{i,t+1}^{j}}{X_{i,t+1}^{g}}\right] - \omega_{i,t+1}^{j}\mathrm{E}\left[\frac{X_{i,t+1}^{j}}{X_{t+1}^{g}}\right] + \left(1-\eta_{t+1}^{j}\right)\left(1-\phi\right)s_l\tilde{s}_{t+1}\mathrm{E}\left[R_{i,t+1}^{j}\right]}{s_k - \omega_{t+1}^{g} + \left(1-\tilde{\eta}_{t+1}\right)\left(1-\phi\right)s_l\tilde{s}_{t+1}} \tag{14}$$

$$TK_{i,j}^{x,y} = K_{i,t}^{j} w_t^{y} L_t^{y} \frac{\alpha_x X_{x,t}^{y} p_{x,t} - CT_{x,t}^{y}}{K_{x,t}^{y}} \exp\left(-\upsilon\left|\ln\frac{Y_t^{j}}{Y_t^{y}}\right|+1\right) \tag{15}$$

In Eq. 14, $R_1\left(i,j,t\right)$ is the investing weight under the investment return rate equilibrium, $\omega_{i,t}^{j}$ denotes the ratio of carbon tax levy to the value added of this sector, and ω_t^{g} denotes the ratio of total carbon tax levy to the global value added. In Eq. 15, $TK_{i,j}^{x,y}$ is the capital attractiveness from sector x in country y to sector i in country j. The initial capital flow model can be found in Wang et al. (2016).

2.3 Technological Progress

In this study, technological progress specifically means process technological progress. Process technological progress refers to the production process innovations that lower the intermediate costs of unitary products. Process technological progress is essential to carbon emission reduction, for low carbon technology is included in the process technology. It should be noted that the process technology in this model means the macro intermediate consuming level of sectors, rather than any special production technology.

According to Lorentz and Savona (2008), a stochastic logarithmic technological shock mechanism is adopted in this model for depicting the process technological progress. In this mechanism, every intermediate input coefficient changes by stochastic normal distributing shock for several rounds in each step.

$$\ln\left(a'_{k,j,i,t}\right) = \ln\left(a^*_{k,j,i,t,n-1}\right) - \varepsilon_{j,k,i,t,n}, \varepsilon_{j,k,i,t,n} \in N\left(0; \rho_t^j\right) \tag{16}$$

After one round, a new set of coefficients is generated as $(a'_{1,j,i,t,N}, \ldots, a'_{I,j,i,t,N})$. This new set will be adopted if its unitary cost $\sum_k^J a'_{k,j,i,t} p_{i,t}$ is less than is the present cost, otherwise it will be abandoned. Then, $(a^*_{1,j,i,t,N}, \ldots, a^*_{I,j,i,t,N})$ is the coefficient set in the next step after N rounds.

This process, in which the sector adopts the technologies that lower its cost and abandons the technologies that increase its costs, depicts a sector's self-selection of technology, and reflects the evolution economic mode recognised by Nelson and Winter (1982), that is, from the microcosmic point, the technological progress is the result of the selection of enterprise for profit, rather than being just a slow, incremental process. This mechanism reflects the randomness of and autonomous nature of technological progress and is far closer to reality than are either a learning curve or other measures.

Equation 16 shows that the variance of the technological shock, ρ, depicts the possibility of technological progress and determines the rate of the process technological progress. Wang et al. (2016) introduced an R&D driven mode, in which the possibility of technological progress is related to knowledge capital stock.

$$\rho_t^j = a^\rho \frac{Z_t^j}{Z_t^j + K_t^j} + b^\rho + c_{j,t}^\rho \tag{17}$$

where a^ρ, b^ρ and $c_{j,t}^\rho$ are parameters.

2.4 Data Sources

The basic economic data and parameter values, including initial value added, fixed capitals, intermediate inputs, energy intensions, and capital output elasticity coefficients are obtained from GTAP-8 database. Historical carbon emission intensities are obtained from EIA. Knowledge capital related parameter values are cited from Wang et al. (2012b) and Liu (2013). Table 2 shows R&D investing rates of countries in the baseline.

For simplification, 57 sectors of GTAP-8 are merged into 12, comprising Agriculture (Agri for short), Food Processing (FdPro), Energy (Enrg), Metal and other Minerals (Mtl&Mn), Light Manufacturing (LghtMnfc), Chemical industry (ChemInd), Heavy Manufacturing (HvyMnfc), Construction (Const), Trade and Business

Table 2 R&D investing rates

CHN	USA	JPN	EU	IND	RUS	ODC	HDC	MDC	LDC
0.0141	0.0257	0.0332	0.0165	0.005	0.01	0.018	0.0014	0.0041	0.0016

Services (Trd&Busi), Transport and Communication (Trans&Comm), Insurance and Finance Services (Ins&Fin) and Other Services (OthServ) after considering their energy consumptions and supply characteristics. The world is also divided into 10 countries/regions according to Malik (2013), comprising China (CHN), the United States (USA), Japan (JPN), the European Union (EU), Russia (RUS), India (IND), Other developed countries (ODC), High developing countries (HDC), Middle developing countries (MDC), and Low developing countries (LDC).

3 Limiting Carbon Tax

Despite Hoel's (1996) assertion that the carbon tax rate across sectors of countries should be unique while the commodities flow freely among countries, both global uniform and national independent carbon tax modes are set as Scenarios 1 and 2, respectively, in this section. All the carbon tax policies since 2016 are implemented, and the carbon tax revenues are consumed. In addition, due to limitations of space, the model validations and the outcomes of the baseline scenario of CIECIA are not covered here. They can be obtained from Wang et al. (2016). Due to the uncertainty of the simulation outcomes caused by the stochastic mechanism of the technological progress, every scenario in this study has been simulated 100 times, and the analyses of those scenarios are based on the statistics of those simulations.

3.1 Global Uniform Rate

Figure 1 shows the global uniform limiting carbon tax and its share in global GDP in Scenario 1. As the carbon emission intensities of sectors are continuously lowered by process technological progress, the limiting tax in each step rises from 47 US Dollar (USD)/tC in 2016 to about 830 USD/tC in 2100, rising and maintaining its GDP share around 2.5% after 2040. Compared with other models, this curve lies almost between the 2 °C carbon tax curves of DICE/RICE and of REMIND (Edenhofer and Kalkuhl 2011). However, it shows that the global temperature in 2100 rises by about 2.46 °C (Table 3) from the pre-industrial level, revealing failure of climate change mitigation. This is partly because the carbon tax in Scenario 1 begins in 2016, 10 years later than in the above studies.

Figure 2 shows the changes of product prices in 2100 under Scenario 1. Compared with the baseline, the prices of four high-emission sectors, Enrg, Mtl&Mn, ChemInd, and Trans&Comm, rise relatively. Among these, the product price of Enrg, which consumes most of the energy during simulation, rises by 35%, followed by ChemInd,

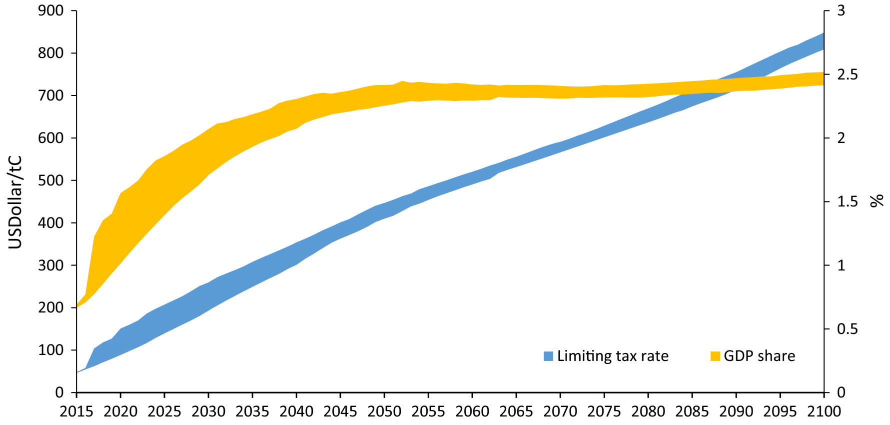

Fig. 1 Limiting carbon tax rate (USD/tC) and the share of carbon tax in global GDP (%) in Scenario 1. The range represents 95% scenario uncertainty

Table 3 Global temperature rise in 2100 from the pre-industrial level (°C) in Scenario 1, and the prediction interval of uncertainty

Mean	50% prediction interval	95% prediction interval
2.4649	2.4515–2.4759	2.4204–2.5021

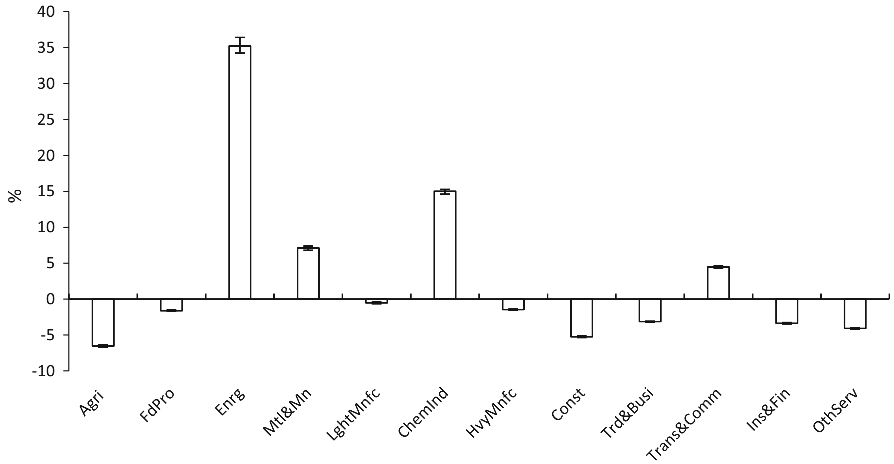

Fig. 2 Changes of relative prices of products by 2100 from the baseline to Scenario 1 (%). *Bars* indicate mean across the simulations. *Error bars* represent 95% prediction interval of scenario

whose price rises by 15%. The prices of Mtl&Mn and Trans&Comm increase by 7.28 and 4.51%, respectively.

Figure 3 depicts the changes of accumulated utilities and carbon emissions from the baseline to Scenario 1 during simulation. The implementation of carbon tax reduces carbon emissions of countries both considerably and effectively. India reduces 70%

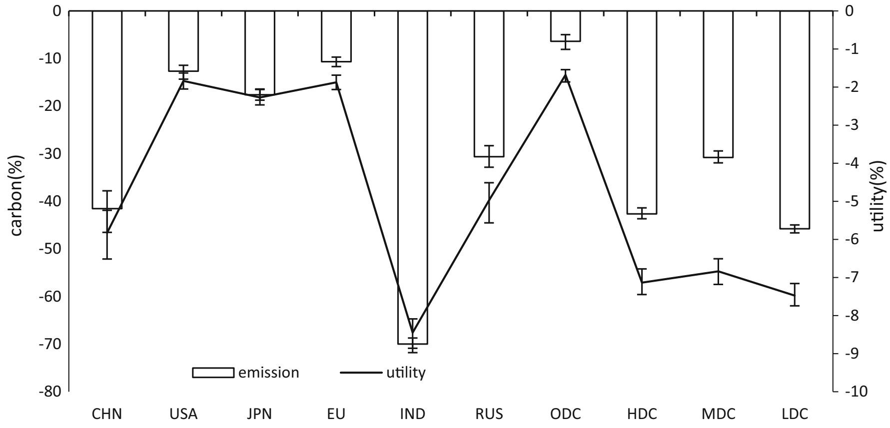

Fig. 3 Changes of accumulated utilities and carbon emissions from the baseline to Scenario 1 (%). *Bars* and *lines* indicate mean across the simulations. *Error bars* represent 95% prediction interval of scenario

of its carbon emissions during 2016–2100, and the reductions of China, HDC, and LDC are all more than 40%. However, carbon tax also causes economic losses in all countries. The accumulated utilities in all the countries decline from the baseline.

It is worth noticing that, even under the same tax rate, the carbon tax has obviously less impact in developed countries than in developing countries. The carbon reductions of developed countries in Scenario 1 are below 20%, and their utility losses are around 2%. That is mainly because developing countries, with higher GDP shares of high energy-consumption industrial sectors and lower process technological levels, will always have more carbon emission demands in future. Thus, the developing level determines that carbon tax is more effective and have greater impacts in developing countries.

3.2 National Independent Rate

In Scenario 2, countries determine their own limiting carbon tax independently. Therefore, countries with higher process technological levels raise their carbon taxes. As Fig. 4 shows, the limiting carbon tax rates in Scenario 2 are much higher than is the global one in Scenario 1. In 2100, the tax rate of ODC rises to about 21.7 thousand USD/tC, followed by China and the USA, whose tax rates rise to about 15 thousand USD/tC. Although the tax rates of India and LDC are the lowest in Scenario 2, they reach about 2 thousand USD/tC in 2100, nearly twice the rate in Scenario 1. In this scenario, the global average carbon tax in 2100 is 4 thousand USD/tC, close to the 2 °C curves of MERGE (Edenhofer and Kalkuhl 2011), and the global temperature rise in 2100 decreases to 1.93 °C (Table 4), achieving the global climate mitigation target.

Carbon tax increase also promotes the adoption of low-carbon technology in process technological progress. In Fig. 5, it can be seen that the carbon emission intensities decline obviously in Scenarios 1 and 2. In Scenario 2, China's carbon intensity in

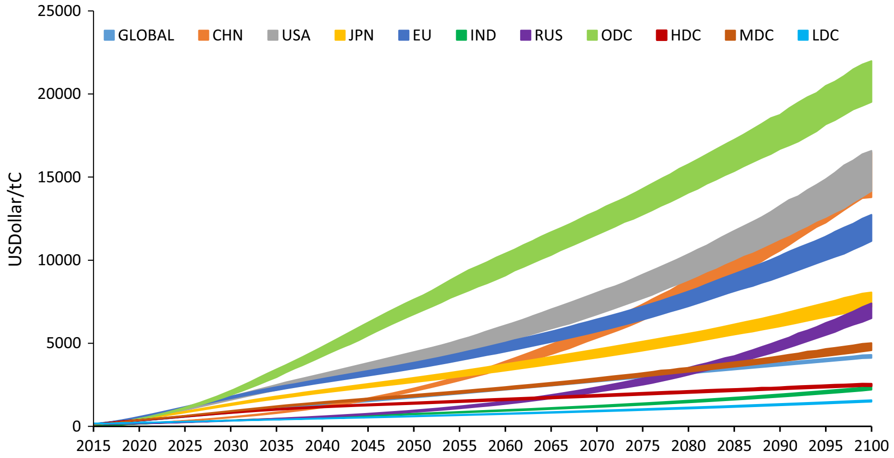

Fig. 4 Range of global average and national independent carbon tax rates in Scenario 2 (US Dollar/tC). The range represents 95% scenario uncertainty

Table 4 Global temperature rise in 2100 from the pre-industrial level (°C) in Scenario 2, and the prediction interval of uncertainty

Mean	50% prediction interval	95% prediction interval
1.9301	1.9280–1.9320	1.9240–1.9366

2100 is less than 0.01 tC/kUSD, close to the levels of the USA, the EU, and Japan. The carbon intensities of India, Russia, HDC, and MDC also drop by more than 50% of their baseline levels. Carbon tax impacts the selection of process technological progress as follows: first, as introduced in Sect. 2.3, the adoption of new process technology depends on its unitary cost; second, as shown in Fig. 2, carbon tax raises the prices of high-emission products; and third, the raised prices of high-emission products increase the unitary costs of high emission process technologies, making low-carbon process technologies more popular with different sectors. The consequent adoption of low-carbon process technologies lowers the carbon intensities during simulation. Therefore, in addition to direct emission control, carbon tax has an indirect reduction effect through sectoral self-selection of process technology.

In Fig. 5, it is worth noticing that the carbon intensity of LDC in Scenario 2 is higher than that in Scenario1. This is because the limiting carbon tax of LDC is much lower than in the other countries in Scenario 2, thereby attracting high-emission sectors that suffer a higher tax hit in other countries, leading to new international industrial transfer trends according to Eqs. 14 and 15. Table 5 shows that the GDP share of Enrg in LDC increases by 30 % points from the baseline to Scenario 2; the shares of other high-emission sectors also increase from Scenario 1. Therefore, the higher share of high-emission sectors increases the carbon intensity of LDC in Scenario 2.

Figure 6 depicts the changes of accumulated utilities and carbon emissions of countries. The carbon reductions of all the countries, apart from Russia and LDC, increase

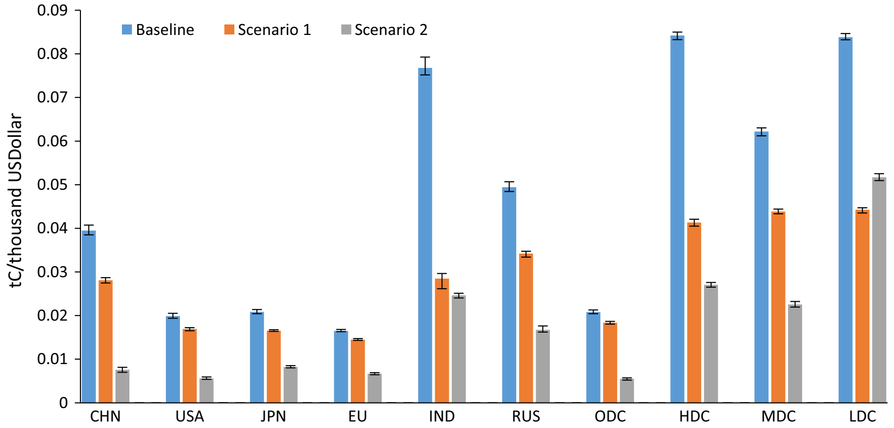

Fig. 5 Carbon emission intensities by 2100 in three scenarios (tC/thousand US Dollar). *Bars* indicate mean across the simulations. *Error bars* represent 95% prediction interval of scenario

Table 5 Mean value of GDP shares of high-emission sectors of LDC by 2100 in three scenarios (%)

	Enrg	Mtl&Mn	ChemInd	Trans&Comm
Baseline	5.38	4.15	2.57	5.73
Scenario 1	7.61	2.18	0.00	3.77
Scenario 2	35.22	3.55	0.02	4.34

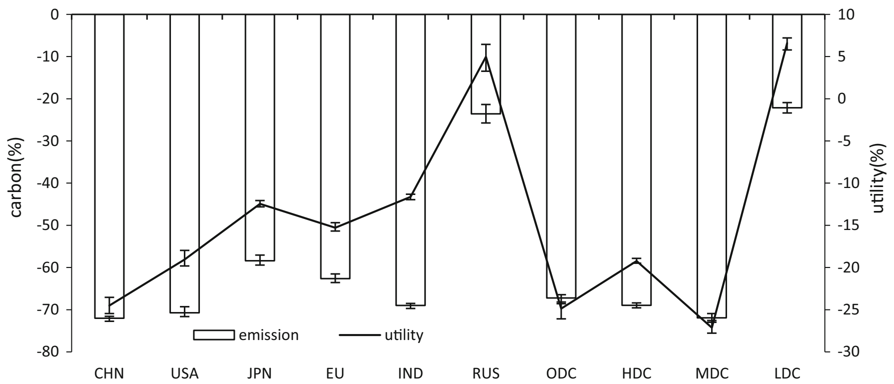

Fig. 6 Changes of accumulated utilities and carbon emissions from the baseline to Scenario 2 (%). *Bars* and *lines* indicate the average value. *Error bars* represent 95% prediction interval of scenario

to 60–70%. The reductions of China and MDC reach as high as 72%. Those of Russia and LDC are relatively lower, only about 23%, but are still higher than are those in Scenario 1. In this scenario, as the price for carbon reduction, China, USA, India, ODC, and MDC lose about one quarter of their accumulated utilities. The utility losses of Japan and the EU are around 20%. Different from other countries, the utilities of Russia and LDC increase in this scenario for higher investment attractiveness caused by lower carbon taxes.

The results show that carbon tax is an effective carbon abatement measure, not only through direct reduction of high-emission products but also through indirect promotion of low-carbon technologies. While the carbon taxes remain national independent, the 2 °C climate mitigation target can be achieved. However, economic loss under carbon taxes cannot be ignored. Considering the current fragile international economic environment, it is hard to image that the world must lose nearly one quarter of its economy for carbon abatement. Moreover, as carbon reductions and economic losses show large differences among countries in Scenarios 1 and 2, carbon tax in this section is still rough and unfeasible. In the next section, we try to complete carbon tax policy by changing the use of tax revenues.

4 Distribution of Carbon Tax Revenue

In this model, carbon tax revenues are distributed in three ways: sectoral production investment, R&D input, and consumption. Among these, the potential benefit of R&D investment is an important reason why carbon tax policy is receiving increasing support (Rees 2006; Schlesinger 2006; IPCC 2007). In this section, a part of the carbon tax revenue is invested in sectoral production and R&D input. The production investment, $CR^I_{j,t}$, is distributed among sectors, based on their carbon intensity.

$$CR^I_{i,j,t} = \frac{X^j_{i,t}/QP^j_{i,t}}{\sum_i^I X^j_{i,t}/QP^j_{i,t}} CR^I_{j,t} \tag{18}$$

Four carbon tax revenue distribution schemes are set out in Table 6. All the tax policies are still implemented from 2016.

Table 7 shows the temperature rise of scenarios. From Scenarios 4 and 6, it can be seen that the additional R&D investments have a significant effect on temperature control. In Scenario 6, 5% more R&D input lowers the global warming to about 1.95 °C in 2100.

Figure 7 depicts the carbon reductions of countries. In Scenarios 3 and 5, carbon emissions increase, as parts of carbon tax revenues are returned to sectors. However, with additional investment of knowledge capitals, countries' carbon emissions decline dramatically. Compared with Scenario 3, most of the countries in Sect. 4 double their carbon reductions, at least. The reduction of ODC increases from 2% in Scenario 3 to 22%. The comparison between Scenario 5 and 6 shows similar results, especially in

Table 6 Carbon tax mode and the use of carbon tax revenues (%)

	Carbon tax mode	Production investment	R&D input	Consumption
Scenario 3	Global uniform	80	0	20
Scenario 4	Global uniform	60	20	20
Scenario 5	National independent	80	0	20
Scenario 6	National independent	75	5	20

Table 7 Global temperature rise in 2100 from pre-industrial level (°C) in four scenarios, and the prediction interval of uncertainty

	Mean	50% prediction interval	95% prediction interval
Scenario 3	2.5749	2.5722–2.5782	2.5649–2.5837
Scenario 4	2.1399	2.1357–2.1472	2.1248–2.1528
Scenario 5	2.1429	2.1414–2.1441	2.1384–2.1499
Scenario 6	1.9561	1.9546–1.9581	1.9509–1.9610

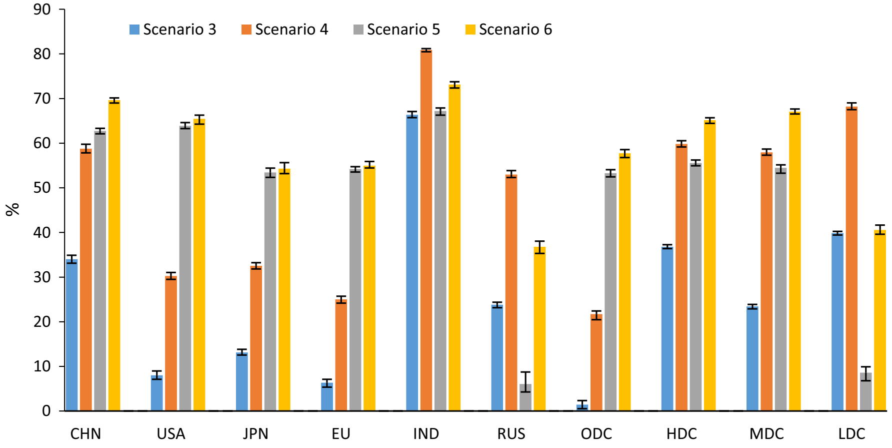

Fig. 7 Carbon reductions of countries in four scenarios. *Bars* indicate mean across the simulations. *Error bars* represent 95% prediction interval of scenario

Russia and LDC. That is because their lower carbon tax rates under the national independent mode results in the agglomeration of high-emission sectors in these countries, while carbon tax revenues are invested back, which brings higher carbon reduction potentials.

It is worth noticing that the carbon reduction increases of developed countries from Scenario 3 to Scenario 4 are higher than are those of developing countries, whereas those from Scenario 5 to Scenario 6 are lower. That is because the changes of global capital flow under a different carbon tax mode. Table 8 shows that under a global uniform carbon tax, developed countries can draw more investments for high-emission sectors, via their more advanced low-carbon technologies, to lower tax levy burdens. The reduction potentials of developed countries rise concomitantly. However, under the national independent mode, the advantages of low-carbon technologies in developed countries translate into much higher tax rates, which prevents high-emission sectors from transferring to developed countries and lowers the reduction potentials of developed countries in Scenario 6.

Figure 8 shows the changes of accumulated utilities in the four scenarios. Compared with Scenarios 1 and 2, the utilities of countries increase when the carbon tax revenues are partly invested. For developing countries, R&D investment significantly promotes economic development and eases utility losses, whereas developed countries are rel-

Table 8 Average total investments to high-emission sectors of developed countries in four scenarios (Billion USD)

	Enrg	Mtl&Mn	ChemInd	Trans&Comm
Scenario 3	42,439.33	54,167.09	53,790.58	76,969.09
Scenario 4	17,308.74	43,081.56	39,900.91	56,083.76
Scenario 5	4433.96	29,010.73	24,150.67	26,484.19
Scenario 6	4693.98	29,594.75	25,548.86	27,504.21

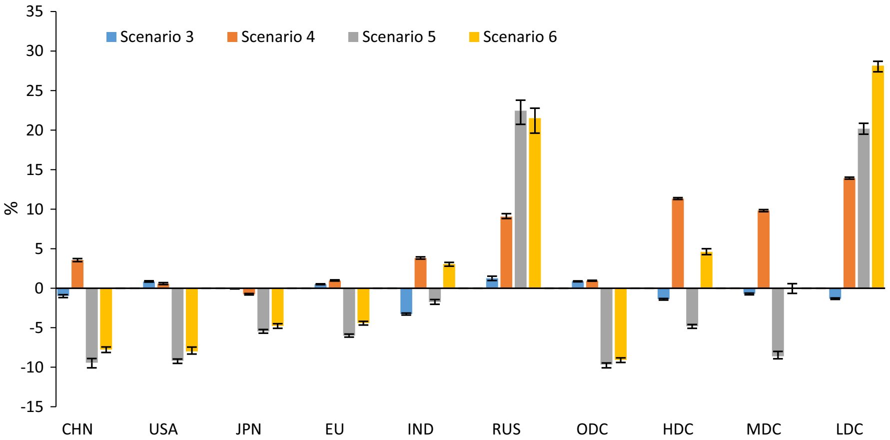

Fig. 8 Accumulated utility changes of countries in four scenarios from the baseline. *Bars* indicate mean across the simulations. *Error bars* represent 95% prediction interval of scenario

atively insensitive. In Scenario 4, the utilities of the USA, Japan, and ODC are even lower than are those in Scenario 3. This is because in Scenario 4, developed countries face fiercer economic competition from developing countries and, thus, obtain fewer investments, which can be proved by Table 8.

In Scenarios 4 and 6, although the utilities of countries are eased by reusing carbon tax revenues, the utilities of some countries are still lower than are their baseline levels, e.g., Japan in Scenario 4, China, and all developed countries in Scenario 6. This means that none of these four scenarios can protect all the countries from economic losses. Thus, these scenarios still lack economic feasibility.

Even so, the results of Scenario 4 and 6 suggest that increasing R&D investment can both ease the economic loss caused by carbon tax and promote further carbon reduction. This indicates that improving technological progress (not only low-carbon technology) should be applied as an important auxiliary measure in reduction schemes.

5 A Pareto-Improving Scheme

Pareto improvement refers to a type of social change to improve the social welfare of some without harming others. From the perspective of welfare, Wang et al. (2014)

noted that a global carbon reduction scheme will not be accepted by all the cooperating countries unless it can benefit all the participants, or at least not harm any of them. In this section, on the basis of the results above, we design a Pareto-improving scheme (Scenario 7) through revenue distribution setting to ensure that the accumulated utilities of all the countries by 2100 are higher than are those in the baseline on the premise of effectiveness that the 2 °C target by 2100 should be achieved. In this scenario, the global uniform mode is adopted, and, to reduce carbon emissions further, all the revenues are invested into three least carbon-intensive sectors, comprising Trd&Busi, Ins&Fin, and OthServ.

$$CR^{I}_{i,j,t} = \frac{X^{j}_{i,t}/QP^{j}_{i,t}}{\sum^{I}_{i\in H} X^{j}_{i,t}/QP^{j}_{i,t}} CR^{I}_{j,t},\ i \in H \tag{19}$$

where H means the set of low carbon-intensive sectors. Moreover, as the economy of developed countries is less sensitive to R&D improvement, and the R&D input rate cannot be raised by too much, a discount of limiting carbon tax is used in this scenario to ensure the Pareto improvement of accumulated utilities. Table 9 lists the carbon tax discounts and the uses of carbon revenues of countries.

Table 10 shows the global warming under Scenario 7. This scenario achieves the climatic effectiveness of a 2 °C global warming target statistically, while the mean value of temperature rise in 2100 across the simulations is 1.99 °C and the 95% prediction interval is located between 1.97 and 2.00 °C.

Figure 9 depicts the changes of accumulated utility from the baseline to Scenario 7. The utilities of all the countries during simulation in this scenario are all higher than are those in the baseline, and the gaps of utility improvements among countries are narrower than in Scenario 4. This means that Scheme 6 realises Pareto improvement of economic impacts under carbon tax policy. According to Wang et al. (2014), such a reduction scheme can be accepted by all the participants. In this regard, Scenario 7 is more economically feasible than are the others.

Table 9 Carbon tax discount and the use of carbon revenues of countries

	CHN	USA	JPN	EU	IND	RUS	ODC	HDC	MDC	LDC
Carbon tax discount (%)	0	20	50	20	0	0	20	0	0	0
Production investment	0.35	0.55	0.45	0.55	0.45	0.45	0.55	0.35	0.35	0.35
R&D input	0.25	0.25	0.35	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Consumption	0.4	0.2	0.2	0.2	0.3	0.3	0.2	0.4	0.4	0.4

Table 10 Global temperature rise in 2100 from the pre-industrial level (°C) in Scenario 7 and the prediction interval of uncertainty

Mean	50% prediction interval	95% prediction interval
1.9906	1.9850–1.9958	1.9786–1.9995

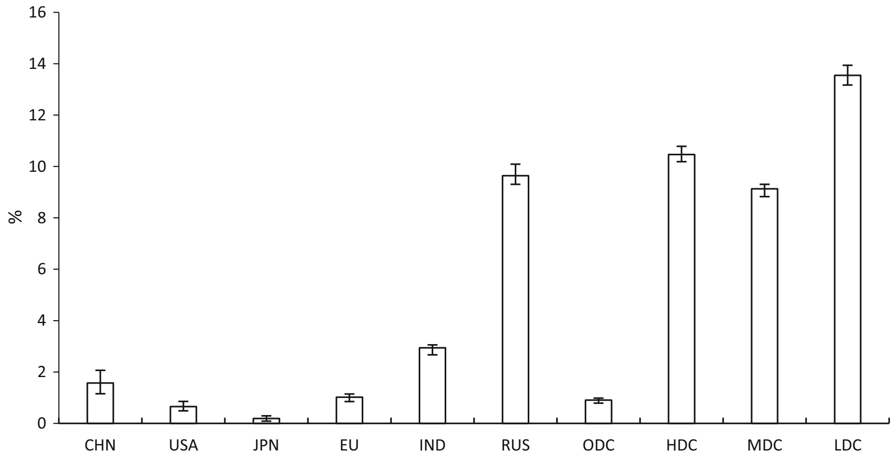

Fig. 9 Accumulated utility changes of countries in Scenario 7 from the baseline. *Error bars* represent 95% prediction interval of scenario

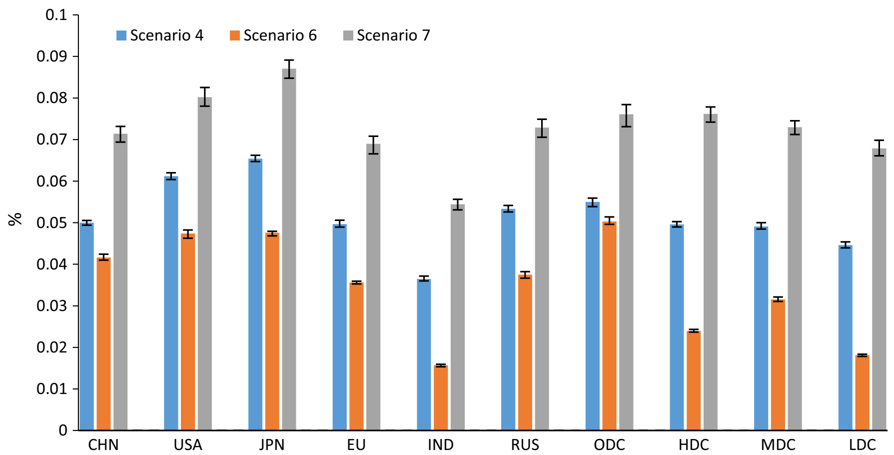

Fig. 10 Shares of R&D inputs in total investments of countries during simulation. *Error bars* represent 95% prediction interval of scenario

Figure 10 shows the average R&D shares of countries in Scenario 7. To achieve both the Pareto improvement of utility and the global warming target, the R&D inputs in this scenario are generally higher than in other scenarios, between 5 and 9%. Considering the current R&D shares of developed countries having been close to 5% and their historical trends, the R&D shares of countries in this scenario are still controlled at an acceptable and realisable level.

6 Conclusions and Discussion

In this study, we built a carbon-tax-integrated version of CIECIA by developing a carbon tax module and integrating it into the standard version to analyse the limit of carbon tax on carbon reduction and climate protection, in addition to its economic and climatic effects. This model includes two types of limiting carbon tax, i.e. global uniform and national independent, and an adjustable carbon tax revenue distribution mode. On the basis of scenario simulations, the carbon reductions and economic effects under limiting carbon taxes were analysed, as were the effects of different tax revenue distributions. Subsequently, a Pareto improving carbon tax scheme that protects the economic benefits of all the participants was presented. The conclusions derived from the scenario simulations were listed as follows.

Carbon tax is an effective measure for carbon emission reduction. It would obviously promote the carbon reductions of countries and improve climate environment greatly. It reduces emissions in two ways: directly, by reducing the incomes of high-emission sectors to reduce their production scales; and indirectly, by promoting the adoption of low-carbon technologies through raising the prices of high-emission products.

Under the global uniform mode, the global limiting carbon tax of CIECIA falls between the 2 °C curves of DICE/RICE and REMIND. However, the global temperature rise by 2100 is about 2.46 °C, which fails to achieve the global climate mitigation target. That is partly because the initiation of carbon tax in this study is 10 years later than in other studies. RICE-2010 shows that, while applying the same starting point and carbon tax curve, the global warming will rise to about 2.3 °C in 2100, quite close to this study. DICE-2013R shows that a similar carbon tax curve will cause a temperature rise in excess of 2.9 °C by 2100. However, considering the much higher baseline temperature projection of RICE-2013 (3.84 °C above pre-industrial), the range of this rise is also close to the result of this study.

The limiting carbon tax under the national independent mode achieves the climate mitigation target by lowering the global warming to about 1.93 °C. The global average curve is close to the 2 °C curve of the MERGE model. Generally, the limiting tax rates of developed countries are much higher than are those of developing countries for their lower carbon emission intensities, which indicates the differences in carbon tax tolerance between developed and developing countries.

As the cost of carbon reduction, the implementation of carbon tax also causes economic losses in countries, especially in developing countries, which contribute more carbon reductions under the same tax rate. This is mainly because developing countries such as China and India will still be in an industrialisation stage in the future and have higher emission demands for their higher carbon emission intensities and faster economic growth rates.

When using carbon tax revenues, it can be seen that improving R&D investment to promote knowledge capital accumulation and process technological progress is an effective way to both reduce carbon emission further and ease economic loss. On the basis of this, coupled with a carbon tax discount for developed countries, we designed a Pareto-improving scheme of carbon tax, under which all the economic benefits of countries are promised and the global temperature rise is controlled under 2 °C under the condition of keeping the R&D investing rates of countries within an acceptable range. It is worth noticing that Scenario 7 meets the climatic effectiveness, economic acceptability, and technological feasibility of carbon tax, but further discussion over whether it is ethically reasonable enough to give developed countries a discounted carbon tax for meeting Pareto improvement is needed. This is beyond the scope of our discussion, as solving this problem requires a much more complex combination of low carbon policies, whereas carbon tax and its use in technological progress are the only measures we adopt in this study.

This study focused on the limit of carbon tax levy and its economic feasibility. Therefore, the process technological progress here only refers to the decline of the entire unitary cost of sectors on a macro level, to reflect the overall improvement of production progress in general. The specialised investment and development of individual CO_2 reduction or removal technologies, such as carbon capture, utilisation, and storage, are not considered. That is, the low-carbon technology mentioned in this study differs from those special reduction technologies. This is a main limitation of this study, and it effects the outcomes somewhat because plenty of effective and low cost technologies have emerged in recent years and reduced the cost of carbon abatement greatly (Socolow et al. 2011; Kheshgi et al. 2012; IPCC 2014). Thus, in further study, we should include the important special low carbon technologies in this model. In addition, we should depict the selection behaviour of sectors between carbon tax penalty and low carbon technology implementation. We leave these topics for our further work.

Acknowledgements This work was supported by Chinese National Natural Science Foundation (Grant No. 41501130) and the National Basic Research Program of China (Grant No. 2012CB955800).

References

Abel, A. B. (2003). The effects of a baby boom on stock prices and capital accumulation in the presence of social security. *Econometrica*, *71*(2), 551–78.

Avi-Yonah, R. S., & Uhlmann, D. M. (2009). Combating global climate change: Why a carbon tax is a better response to global warming than cap and trade. *Stanford Environmental Law Journal*, *28*(1), 3–50.

Baranzini, A., Goldemberg, J., & Speck, S. (2000). A future for carbon taxes. *Ecological Economics*, *32*(3), 395–412.

Brandt, U. S., & Svendsen, G. T. (2014). A global CO_2 tax for sustainable development? *Journal of Sustainable Development*, *7*(1), 85–93.

Cai, Y., Judd, K. L., & Lontzek, T. S. (2012). The social cost of stochastic and irreversible climate change, Working Paper 18704, NBER, Cambridge, MA.

Edenhofer, O., & Kalkuhl, M. (2011). When do increasing carbon taxes accelerate global warming? A note on the green paradox. *Energy Policy*, *39*, 2208–2212.

Elliott, J., Foster, I., Kortum, S., Munson, T., Cervantes, F. P., & Weisbach, D. (2010). Trade and carbon taxes. *The American Economic Review*, *100*(2), 465–469.

Hoel, M. (1996). Should a carbon tax be differentiated across sectors? *Journal of Public Economics*, *59*(1), 17–32.

IPCC. (2007). Climate Change 2007: Mitigation of Climate Change. http://www.ipcc.ch/report/ar4/wg3/.

IPCC. (2014). Climate Change 2014: Mitigation of Climate Change. http://www.ipcc.ch/report/ar5/wg3/.

Jin, K. (2012). Industrial structure and capital flows. *American Economic Review*, *102*(5), 2111–2146.

Kheshgi, H. S., Thomann, H., Bhore, N. A., Hirsch, R. B., Parker, M. E., & Teletzke, G. (2012). Perspectives on CCS cost and economics. *SPE Economics & Management*, *4*, 24–31.

Leimbach, M., Bauer, N., Baumstark, L., Luken, M., & Edenhofer, O. (2010). Technological change and international trade—Insights from REMIND-R. *Energy Journal*, *31*(special issue 1), 109–136.

Lemoine, D., & Traeger, C. (2014). Watch your step: Optimal policy in a tipping climate. *American Economic Journal: Economic Policy*, *6*(1), 137–166.

Liu, C. (2013). The construction of a new style of IAM and study on the global corporations for the mitigation of the carbon dioxide. Doctoral degree dissertation. University of Chinese Academy of Sciences, Beijing.

Lorentz, A., & Savona, M. (2008). Evolutionary micro-dynamics and changes in the economic structure. *Journal of Evolutionary Economics*, *18*(34), 389–412.

Malik, K. (2013). *The 2013 human development report—The rise of the south: Human progress in a diverse world*. New York: United Nations Development Program.

Manne, A. S., & Richels, R. G. (2006). The role of non-CO_2 greenhouse gases and carbon sinks in meeting climate objectives. *The Energy Journal (Multi-Greenhouse Gas Mitigation and Climate Policy, Special Issue No. 3)*, *3*, 393–404.

Nelson, R. R., & Winter, S. G. (1982). *An evolutionary theory of economic change*. Cambridge: The Belknap Press of Harvard University Press.

Nordhaus, W. D. (2008). *A question of balance: Weighing the options on global warming policies*. New Haven: Yale University Press.

Nordhaus, W. D., & Yang, Z. (1996). RICE: a regional dynamic general equilibrium model of optimal climate-change policy. *The American Economic Review, 86*(4), 741–765.

Pearce, D. (1991). The role of carbon taxes in adjusting to global warming. *The Economic Journal*, *101*(407), 938–948.

Rees, M. (2006). The G8 on energy: Too little. *Science*, *313*, 591.

Schlesinger, W. (2006). Carbon trading. *Science*, *314*, 1217.

Socolow, R. H., Desmond, M., Aines, R., Blackstock, J., Bolland, O., Kaarsberg, T., et al. (2011). *Direct air capture of CO_2 with chemicals: A technology assessment for the APS panel on public affairs*. Washington, DC: The American Physical Society.

Svirezhev, Y., Brovkin, V., Bloh, W., Schellnhuber, H. J., & Petschel-Held, G. (1999). Optimisation of reduction of global CO_2 emission based on a simple model of the carbon cycle. *Environmental Modeling and Assessment*, *4*, 23–33.

Wang, Z., Gu, G., Wu, J., & Liu, C. (2016). CIECIA: A new climate change integrated assessment model and its assessments of global carbon abatement schemes. *Science China: Earth Sciences*, *59*, 185–206.

Wang, Z., Liu, X., Tian, Y., et al. (2014). Several issues of climate change ethics. *Scientia Sinica Terrae*, *44*, 1600–1608.

Wang, Z., Wu, J., Zhu, Q., Wang, L., Gong, Y., & Li, H. (2012a). MRICES: A new model for emission mitigation strategy assessment and its application. *Journal of Geographical Sciences*, *22*(6), 1131–1148.

Wang, Z., Zhang, S., & Wu, J. (2012b). A new RICEs model with the global emission reduction schemes. *Chinese Science Bulletin*, *57*, 4373–4380.

Zhang, Z., & Baranzini, A. (2004). What do we know about carbon taxes? An inquiry into their impacts on competitiveness and distribution of income. *Energy Policy*, *32*(4), 507–518.