Modelling the impacts of a national carbon tax in a country with inhomogeneous regional development: an actor-based system-dynamic approach

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Abstract

We present a family of simple globally aggregated and regionalized actor-based system-dynamics Integrated Assessment models (IAMs). We first develop a global IAM in which both fossil-fuel-based capital and renewable-energy-based capital determine the production function. A business-as-usual scenario (no mitigation policy) is compared with various mitigation scenarios based on different global carbon tax rates. The basic model is then extended to a regionalized IAM consisting of a large country composed of two regions characterized by different climates and levels of economic development coupled to large residual "country" representing the "rest of the world". A harmonized carbon tax is imposed in both regions of the country and as well as in the rest of the world. We explore to which extent inter-regional disparities in economic development and climate change impacts can be alleviated by a national government through the inter-regional transfer of income from carbon tax revenues.

Keywords: actor-based modelling, system dynamics, climate change, mitigation, carbon tax, multi-region models, inhomogeneous regional development

JEL codes: Q54, O44, R11

1 Introduction

Different countries can be affected very differently by the adverse impacts of anthropogenic climate change. For a large country consisting of several geographically distinct regions, the direct geographical impacts of climate change can already differ significantly. Given the inhomogeneous regional economic development typical for many large countries, it can then be anticipated that the existing regional economic disparities will increase still further as global warming develops. It is thus important that the impacts of climate mitigation policies are assessed not only on global and national levels, but also on the regional level.

The key tool for assessing the efficiency of climate mitigation policies and their impacts are Integrated Assessment models (IAMs), i.e. dynamic models of the coupled climate–socioeconomic system.[1] The family of IAMs described in the present paper represent extensions and modifications of a set of actor-based system-dynamics models reported earlier.[2] The models focus on the strategies of key decision-making aggregate economic actors (often pursuing conflicting goals) that jointly govern the dynamic evolution of the socio-economic system.[3]

The paper is organized as follows. Sec. 2 starts with a global IAM in which both fossil-fuel-based capital and renewable-energy-based capital determine the production function. We compare a business-as-usual scenario (no mitigation policy) with various mitigation scenarios based on different global carbon tax rates. The revenues from the carbon tax are recirculated into the economy in the form of investments in renewable-energy-based capital. We explore both the case of constant productivity of renewable-energy-based capital and the case with endogenous improvements of renewable-energy productivity through learning-by-doing effects. The model simulations demonstrate that efficient mitigation policies are feasible at readily affordable costs.

From this we develop in Sec. 3 a regionalized IAM using the same methodological approach. We consider a large country composed of two regions characterized by different climates and levels of economic development. This is coupled to large residual "country" representing the "rest of the world". It is assumed that a harmonized carbon tax is imposed in both regions

[1] Nordhaus W.D. (2008), *A Question of Balance*, Yale University Press, New Haven & London.

[2] Hasselmann K. (2013), Detecting and responding to climate change, Tellus B 65, 20088, http://dx.doi.org/10.3402/tellusb.v65i0.20088 (open access).

[3] Hasselmann K., Kovalevsky D.V. (2013), Simulating animal spirits in actor-based environmental models, Environmental Modelling & Software 44, 10–24.

of the country and also in the rest of the world. We explore the extent to which a national government can moderate regional disparities in economic development and climate change impacts between the two regions by the transfer of income from carbon tax revenues.

Sec. 4 concludes.

2 A simple aggregate Integrated Assessment model

2.1 Model equations

The following model is essentially a modification of the simplest member of a family of models reported earlier.[4] It describes the growth of an aggregate world economy coupled to the global climate system.

The production function depends on two production factors: fossil-fuel-based capital K and renewable-energy-based capital R. We assume an additive form

$$Y = \mu_K K + \mu_R R \tag{1}$$

for the output Y of the global economy, where μ_K and μ_R are the productivities of fossil-fuel-based and renewable-energy-based capital, respectively.

We assume μ_K to be constant. For μ_R we explore two alternative scenarios: either μ_R is also constant, and is always less than μ_K: $\mu_R < \mu_K$, or μ_R can be endogenously improved by learning-by-doing effects (see Eq. (13) below). In the latter case, the initial value of μ_R (μ_{R0}) is again less than μ_K ($\mu_{R0} < \mu_K$), but its asymptotic value as $t \to +\infty$ can well exceed μ_K: $\mu_{R\infty} > \mu_K$.

The total output Y can be subdivided into the production of fossil-fuel-based capital Y_K (equal to the investment in fossil-fuel-based capital), the production of renewable-energy-based capital Y_G (equal to investment in renewable-energy-based capital), and — the ultimate goal of the economy — the production of consumer goods and services Y_G (referred to in the following

[4] Hasselmann K. (2013), Detecting and responding to climate change, Tellus B 65, 20088, http://dx.doi.org/10.3402/tellusb.v65i0.20088 (open access).

simply as consumer goods):[5]

$$Y = Y_K + Y_R + Y_G. \tag{2}$$

For the following, we assume that the production of consumer goods represents a constant fraction of total output:

$$Y_G = \rho_G Y, \qquad \rho_G = \text{const}, \tag{3}$$

so that, from Eq. (2),

$$Y_K + Y_G = (1 - \rho_G)Y. \tag{4}$$

Use of fossil-fuel-based capital K produces carbon emissions E

$$E = \alpha K, \tag{5}$$

which we set proportional to K, with $\alpha = \text{const}$.

In the mitigation scenarios considered below a global carbon tax is imposed on emissions, with a tax rate τ, yielding carbon tax revenues

$$\Theta = \tau E \tag{6}$$

(in the business-as-usual scenario, $\tau = 0$).

As individual producers are generally not motivated to invest in renewable-energy-based capital while $\mu_R < \mu_K$, we assume that the carbon tax revenues are recirculated into the economy in the form of subsidies for renewable-energy-based capital:

$$Y_R = \Theta. \tag{7}$$

Thus, from Eq. (4),

$$Y_K = (1 - \rho_G)Y - \Theta. \tag{8}$$

For the scenario with $\mu_R = \text{const}$, the inequality $\mu_R < \mu_K$, and therefore the imposition of a carbon tax, holds for all time. For the alternative scenario with an endogenously growing renewable-energy-efficiency μ_R, however, Eqs. (7)-(8) hold only until a time $t = t^*$ at which

[5] Since we have excluded disequilbrium effects such as idle capital, unemployment, non-cleared consumer-goods markets, or financial market instabilities (discussed in the earlier work cited), all production components can be expressed in non-money material or "goods" units.

$\mu_R(t^*) = \mu_K$. For $t > t^*$, individual producers become motivated to invest in renewable-energy-based capital without an additional subsidy, so that the carbon tax can be cancelled. Thus, for $t > t^*$ we have

$$Y_K = 0, \tag{9}$$

$$Y_R = (1 - \rho_G)Y. \tag{10}$$

Eq. (9) implies that fossil-fuel-based capital becomes uncompetitive and starts decreasing, all investment now being channeled into renewable-energy-based capital.

The dynamics of both forms of capital is described by the standard equations

$$\dot{K} = Y_K - \lambda_K K, \tag{11}$$

$$\dot{R} = Y_R - \lambda_R R, \tag{12}$$

where λ_K and λ_R represent the depreciation rates of fossil-fuel based and renewable-energy-based capital, respectively.

In the learning-by-doing scenario, we assume as heuristic dynamic equation for endogenous improvement of renewable-based-capital productivity

$$\dot{\mu}_R = c\left(1 - \frac{\mu_R}{\mu_R^{\max}}\right) Y_R. \tag{13}$$

where $c = \mathrm{const}$ and $\mu_R^{\max} > \mu_K$. Note that $\mu_R \to \mu_R^{\max}$ as $t \to +\infty$. (The scenario with constant μ_R corresponds to $c = 0$ in Eq. (13)).

We also adopt a very simple climate module in a from of dynamic equation for global mean temperature T:

$$\dot{T} = E - \lambda_T T \tag{14}$$

where λ_T is the temperature adjustment rate.

Finally, as in the earlier version of the model,[6] we assume that global welfare is equal to the production of consumer goods, corrected by a factor that takes into account adverse climate change impacts:

$$W = Y_G \exp(-\alpha_* T^2). \tag{15}$$

[6]Ibid.

In summary, the full dynamic system is given by:

$$\dot{K} = Y_K - \lambda_K K, \tag{16}$$

$$\dot{R} = Y_R - \lambda_R R, \tag{17}$$

$$\dot{\mu}_R = c\left(1 - \frac{\mu_R}{\mu_R^{\max}}\right) Y_R, \tag{18}$$

$$\dot{T} = \alpha K - \lambda_T T, \tag{19}$$

$$Y = \mu_K K + \mu_R R \tag{20}$$

$$Y_K = (1-\rho_G)Y - \tau\alpha K, \qquad Y_R = \tau\alpha K \qquad \text{for} \quad \mu_R < \mu_K, \tag{21}$$

$$Y_K = 0, \qquad Y_R = (1-\rho_G)Y \qquad \text{for} \quad \mu_R > \mu_K, \tag{22}$$

with initial conditions

$$K(t=0) = K_0, \tag{23}$$

$$R(t=0) = 0, \tag{24}$$

(we assume there exists no stock of renewable-energy-based capital initially)

$$\mu_R(t=0) = \mu_{R0}, \tag{25}$$

$$T(t=0) = T_0, \tag{26}$$

and a climate-dependent welfare function

$$W = Y_G \exp(-\alpha_* T^2). \tag{27}$$

2.2 Simulation results

2.2.1 Business-as-usual scenario

We consider first the business-as-usual scenario (no mitigation policy, carbon tax rate $\tau = 0$).

Equations (17), (21) and (24), imply that in this case renewable-energy-based capital will never emerge: $R(t) = 0$ for all $t > 0$. From Eqs. (16), (20), and (21) we can then derive a closed linear ODE for fossil-fuel-based capital dynamics:

$$\dot{K} = \left[(1-\rho_G)\mu_K - \lambda_K\right] K \tag{28}$$

with the solution

$$K = K_0 \exp(\lambda_0 t) \tag{29}$$

where

$$\lambda_0 = (1 - \rho_G)\mu_K - \lambda_K \tag{30}$$

represents the economic growth rate.

Substitution of the solution (29) into Eq. (19) yields another linear ODE for the temperature

$$\dot{T} = \alpha K_0 \exp(\lambda_0 t) - \lambda_T T \tag{31}$$

with the solution

$$T = \frac{\alpha K_0}{\lambda_0 + \lambda_T} \exp(\lambda_0 t) + \left(T_0 - \frac{\alpha K_0}{\lambda_0 + \lambda_T}\right) \exp(-\lambda_T t). \tag{32}$$

Thus output grows exponentially, and temperature also increases asymptotically at the same exponential rate. The latter implies that, despite economic growth, welfare W, as defined by Eq. (27), rapidly converges to zero as $t \to \infty$.

2.2.2 Mitigation scenario, $\mu_R = \mathrm{const}$

We now assume that a carbon tax is imposed ($\tau > 0$), but with $\mu_R = \mathrm{const}$ (no learning-by-doing, $c = 0$ in Eq. (18)).

In this case, Eqs. (16)-(17), (20)-(21) can be rewritten as a two-dimensional linear dynamic system in matrix from:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} \tag{33}$$

where $\mathbf{x}(t)$ is the state vector

$$\mathbf{x} = \begin{pmatrix} K \\ R \end{pmatrix} \tag{34}$$

and $\mathbf{A}$ is a constant matrix of the form

$$\mathbf{A} = \begin{pmatrix} (1 - \rho_G)\mu_K - \tau\alpha - \lambda_K, & (1 - \rho_G)\mu_R \\ \tau\alpha, & -\lambda_R \end{pmatrix}. \tag{35}$$

In matrix notation, the solution of Eq. (33) is

$$\mathbf{x}(t) = \exp(\mathbf{A}t)\mathbf{x}_0, \tag{36}$$

or, explicitly,

$$\mathbf{x}(t) = \mathbf{c}_1 \exp(\lambda_1 t) + \mathbf{c}_2 \exp(\lambda_2 t) \tag{37}$$

where λ_1 and λ_2 represent the eigenvalues of the matrix $\mathbf{A}$, and $\mathbf{c}_1$ and $\mathbf{c}_2$ the associated eigenvectors.

Thus the fossil-fuel-based capital $K(t)$ consists of a linear combination of two exponents. Substitution of K into the temperature equation (19), yields as solution of the resultant linear ODE;

$$T = \theta_1 \exp(\lambda_1 t) + \theta_2 \exp(\lambda_2 t) + \theta_T \exp(-\lambda_T t) \tag{38}$$

where θ_1, θ_2 and θ_T are constant factors depending on the initial conditions. Again, both forms of capital and temperature grow exponentially. Although the mitigation policy reduces the temperature growth rate, ultimately the welfare converges to zero, as in the business-as-usual scenario (Sec. 2.2.1).

2.2.3 Mitigation scenario, learning-by-doing

Finally, we explore mitigation scenarios with endogenous renewable-energy-based capital productivity improvement. We take $\mu_{R0} = 0$ as initial condition, but assume that now that the learning-by-doing parameter $c > 0$ in Eq. (18). In this model setup, exact analytical solutions are no longer possible due to the pronounced nonlinearity of the system. However, numerical simulation results are presented in Fig. 1: black curves correspond to the reference case of business-as-usual scenario considered in Sec. 2.2.1; red curves correspond to a low carbon tax rate, green curves to a high carbon tax rate.

As indicated previously, a shift in the mitigation regime occurs at $t = t^*$, where $\mu_R(t^*) = \mu_K$. In Fig. 1a, fossil-fuel-based capital starts decaying at this point, while in Fig. 1c renewable-energy-based capital productivity exhibits a discontinuity in growth rate at the same point. The high carbon tax rate scenario is seen to be highly efficient in averting dangerous climate change (Fig. 1d) and yields encouraging long-term projections of welfare (Fig. 1f).

3 A regionalized Integrated Assessment model

We extend now our model to a regionalized IA model by introducing a two-level hierarchical decomposition of the world economy. At the upper level, we distinguish between "a large country" and "the rest of the world". At the lower level, we distinguish between two regions in a country characterized by different stages of economic development and different vulnerability to climate change. We refer to the wealthier region with less vulnerabilty to climate change as the "rich" region (subscript "1"), the remaining region as the "poor" region (subscript "2"); the rest of the world is denoted by the subscript "3".

To build this regionalized model, the major part of equations of the basic system presented in Sec. 2.1 (Eqs. (16)-(27)) need simply to be triplicated.

We consider first the autarkic case when there are no direct economic interactions between any two of three model regions. The regions are then connected only indirectly, through the global climate system. Equations (16)-(18), (20)-(27) need then to be simply triplicated by assigning subscripts 1, 2, 3 to all variables and parameters, while the temperature equation (19) needs to be generalized to account for emissions from all three regions:

$$\dot{T} = \alpha_1 K_1 + \alpha_2 K_2 + \alpha_3 K_3 - \lambda_T T. \tag{39}$$

We assume that all numeric values of all parameters for all three regions (including carbon tax rate harmonized across three regions) are identical, with the following two exceptions:

(i) The initial values for fossil-fuel-based capital in the three regions are defined in the ratios 8:2:90 (rich region: poor region: "rest of the world").

(ii) The poor region is assumed to be more severely affected by adverse climate change than the rich region and the rest of the world. Thus in the welfare functions (Eq. (27)) we adopt the following values for the model parameter α_*:

$\alpha_{1*} = 0.1$ (°C)$^{-2}$ (rich region);

$\alpha_{1*} = 0.2$ (°C)$^{-2}$ (poor region);

$\alpha_{1*} = 0.1$ (°C)$^{-2}$ (rest of the world).

Fig. 2 presents the welfare dynamics in the rich and poor regions for the same three scenarios as in Sec. 2 (business-as-usual, low carbon tax rate, high carbon tax rate) for the autarkic case. In neither of the two mitigation scenarios is the growth of $\mu_R(t)$ sufficient (within the simulation time span of 150 years) to exceed μ_K, since the absolute value of the investment in renewable-energy-based capital is substantially lower in both regions than in the rest of the world (which is set at the same value as in the previous globally aggregated model). As in the case of the aggregated model, the high carbon tax rate provides the most favourable projections in the long run. However, towards the end of the simulation time span (150 years), the disparities between the rich and poor regions, initially due to different endowments of fossil-fuel-based capital at $t = 0$, are increased substantially due to the more pronounced impacts of climate change in the poor region.

We consider now the case of a national policy devised to achieve a convergence of economic development in the two regions. We assume that some fraction (up to 100 per cent) of carbon tax revenues collected in the rich region is transferred to the poor region and invested there in renewable-energy-based capital. Although the two regions of the country are no longer autark with respect to each other, the two-region country as a whole is still a closed economy with respect to the rest of the world.

To represent the transfer of the carbon tax revenues from the rich to the poor regions the regional equations Eqs. (21)-(22) need to be appropriately modified.

The simulations presented on Fig. 3 correspond to the case of a full transfer of carbon tax revenues from the rich to the poor region, for a high carbon tax rate scenario. A high carbon tax rate scenario is beneficial in the long term for all regions, and provides a strong moderation of regional disparities by means of redistribution of carbon tax revenues in favour of less advanced regions.

4 Conclusions

Our simple regionalized Integrated Assessment model has addressed the impacts of a carbon tax and its redistribution in the form of subsidies for investments in renewable energy on the economic development and welfare of the three different economic regions. Both the economic and the climate module of the coupled climate—economy model are extremely simple. Thus the economic regions (a large two-region country coupled to the "rest of the world") are treated as basically autark, the coupling occurring only through the (regionally dependent) climate impacts and the redistribution of the carbon-tax-income within the two-region country by a federal government. However, the positive long-term welfare impacts of a carbon tax and its redistribution to counter imbalances of the climate-change impacts and the economic development within the different economic regions have been clearly demonstrated. Further developments of more realistic versions of the model, including international trade and mobility of capital and labour, conflicting goals of different economic and political actors (as explored in previous globally integrated model versions) are feasible and are planned for future research.

Acknowledgements

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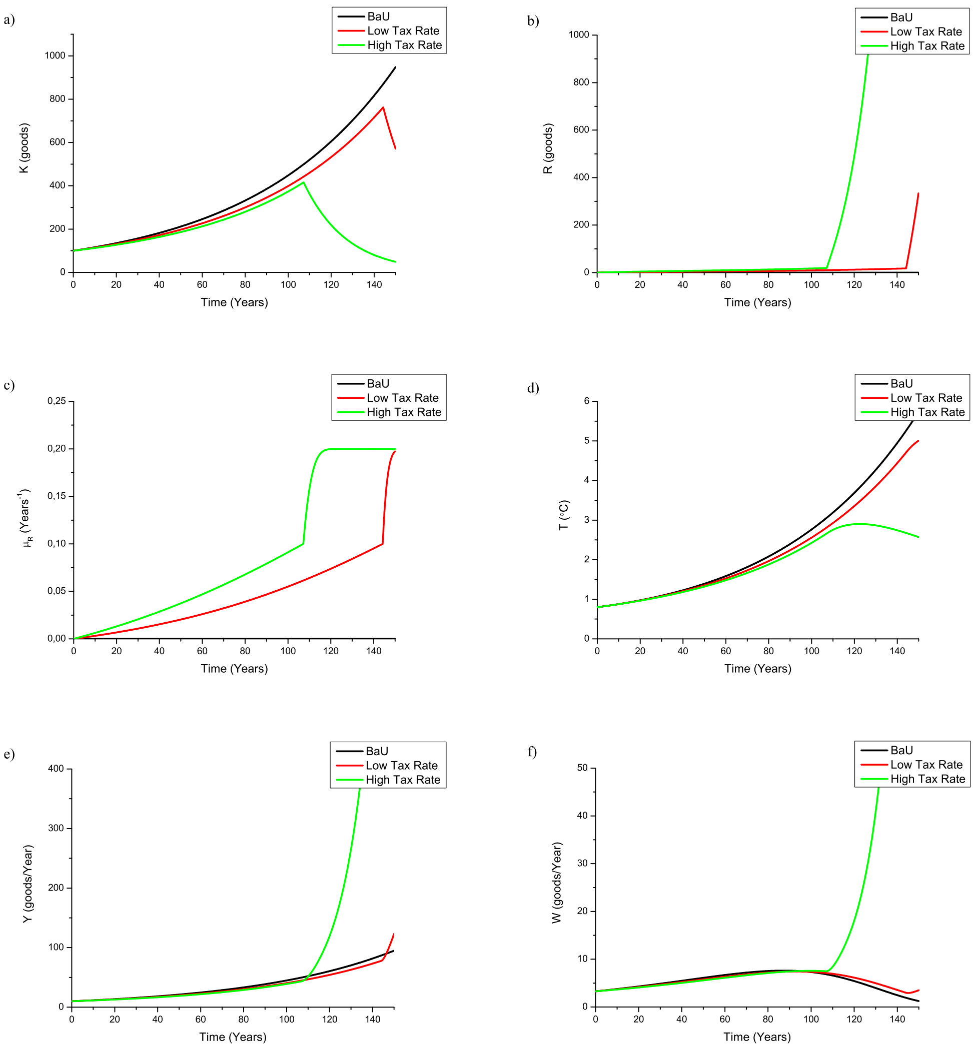

Figure 1: Dynamics of global climate–economic system in the business-as-usual scenario (black curves) and in mitigation scenarios with endogenous renewable-energy-based capital productivity improvement: low carbon tax rate (red curves) and high carbon tax rate (green curves): a) Fossil-fuel-based capital (in mitigation scenarios starts decaying at $t = t^*$ where $\mu_R(t^*) = \mu_K$). b) Renewable-energy-based capital. c) Renewable-energy-based productivity (with mitigation scenario discontinuity of derivative at $t = t^*$ where $\mu_R(t^*) = \mu_K$). d) Global mean temperature. e) Output. f) Welfare.

a)

b)

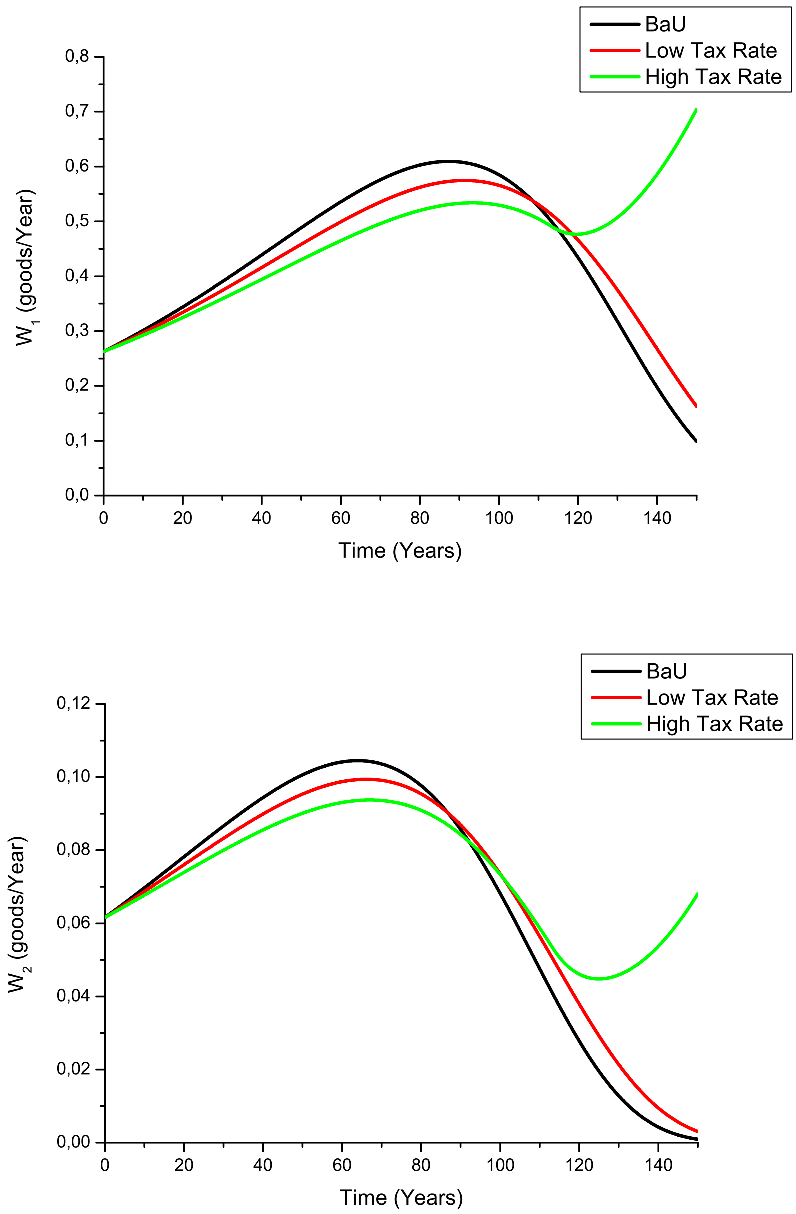

Figure 2: Welfare dynamics in "rich" and "poor" regions of a large country in the business-as-usual scenario (black curves) and in mitigation scenarios with endogenous renewable-energy-based capital productivity improvement: low carbon tax rate (red curves) and high carbon tax rate (green curves). Autarkic case (no transfer of carbon tax revenues between regions): a) "Rich" region. b) "Poor" region.

a)

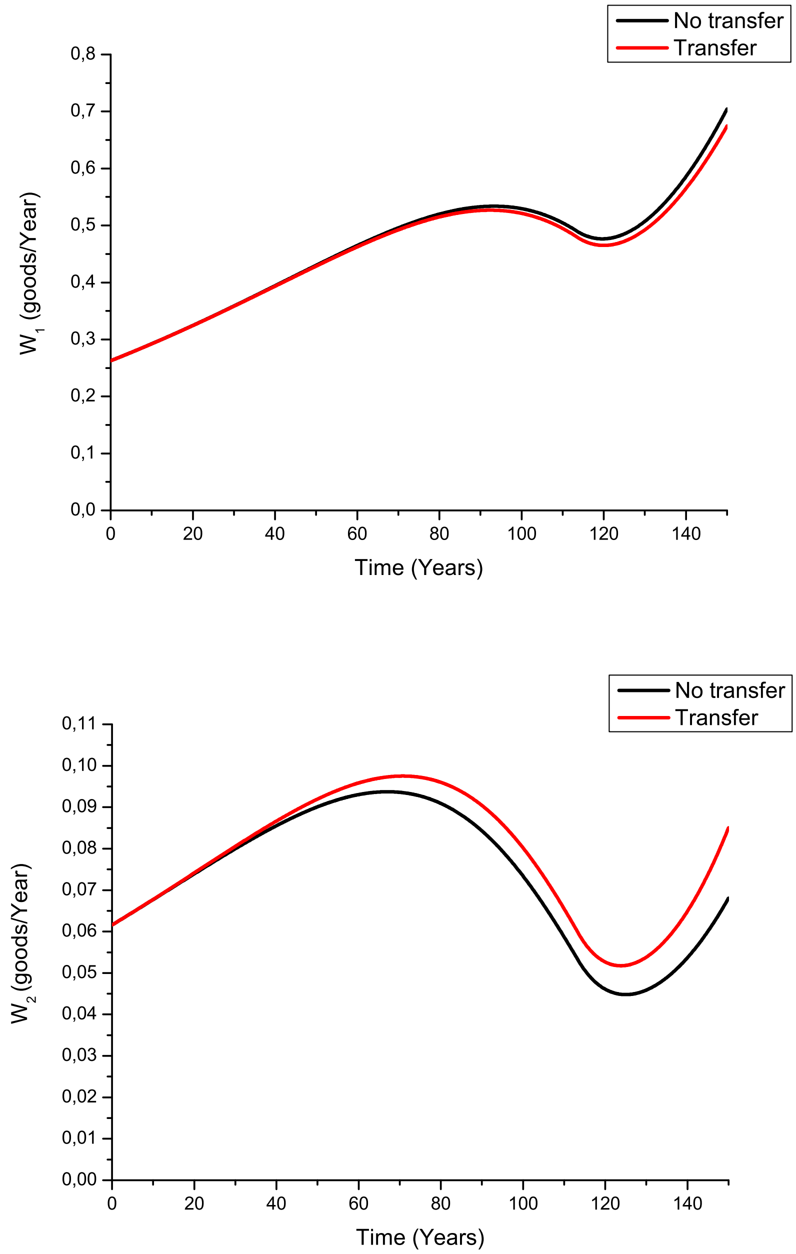

Figure 3: Welfare dynamics in "rich" and "poor" regions of a large country in mitigation scenario with endogenous renewable-energy-based capital productivity improvement under high carbon tax rate. Black curve: case of no transfer of carbon tax revenues between regions. Red curve: full transfer of carbon tax revenues from "rich" to "poor" region: a) "Rich" region. b) "Poor" region.