Diskussionsschriften

Where-to-Abate and Where-to-Invest Flexibility: An Integrated Assessment Analysis of Climate Change

Gunter Stephan and Georg Müller-Fürstenberger

00-01

August 2000

Universität Bern
Volkswirtschaftliches Institut
Gesellschaftstrasse 49
3012 Bern, Switzerland
Tel: 41 (0)31 631 45 06
Web: www-vwi.unibe.ch

‘Where-to-Abate’ And ‘Where-to-Invest’ Flexibility
An Integrated Assessment Analysis of Climate Change

by

Gunter Stephan and Georg Müller-Fürstenberger *
Institute for Applied Micro-Economics
University of Bern

Abstract:

Within the framework of a dynamic Computable General Equilibrium model this paper analyses the impact of trade restrictions on regional rates of return on capital, marginal costs of abatement and optimal climate policy. It will be shown that regional differences both in marginal costs of abatement and in the marginal productivity of capital are driven by market imperfection. With restrictions on international trade, the industrialized countries of the North exhibit higher marginal costs of abatement and a lower marginal productivity of capital than the developing nations of the South. Free trade not only in carbon emission rights but also in capital increases conventional welfare but stimulates carbon dioxide emissions which are not completely offset by efficiency gains in abatement. Nevertheless, depending upon the choice of the discount rate some kind of an invariance result is observed.

JEL Classification: F21, Q25.

Key-words:

Climate policy, carbon emission trade, rate-of-interest differential, marginal cost of abatement, capital mobility, international capital market imperfection.

* Corresponding author: Prof. Dr. Gunter Stephan, Department of Applied Micro-Economics, University of Bern, Gesellschaftsstrasse 49, CH3012 Bern.

1. Introduction

International agreements on greenhouse gas abatement must provide answers to at least two questions: (1) where to abate, and, (2) by how much to abate greenhouse gas emissions? From an economic viewpoint the response to these questions seems almost obvious. Climate change policy should lead to a pareto-efficient internalization of external effects of global warming. Greenhouse gas abatement should primarily take place where costs are lowest, and, to assure efficiency, carbon emission permits should be tradable on open international markets.

These propositions, however, are hardly expected to apply in reality. Since the OECD countries as well as the former Soviet Union are responsible for the majority of both current and past carbon dioxide (CO_2) emissions, developing countries insist that the industrialized nations should take moral responsibility by reducing their CO_2 emissions. In particular, they require that the OECD countries should not be allowed to reduce their abatement duties through trading carbon emission rights.

The industrialized nations, however, counter that marginal costs of greenhouse gas abatement are typically lower in the developing than in the industrialized regions of the world, and that an efficient solution of the global climate problem requires the equalization of marginal costs of abatement (see Weyant, 1997). In their view, curbing greenhouse gas emissions is also to be initiated in the developing countries.

In some way the Kyoto Protocol reflects both views. The so-called ANNEX 1 parties which includes the OECD countries have agreed to abate their carbon emissions first. Additionally, they are at least in principle allowed to trade carbon emission rights among themselves and to opt for joint implementation. By this ANNEX 1 countries might take advantage of low cost abatement potentials.

It is widely accepted among economists that differences in marginal costs of abatement incur efficiency losses. Chichilnisky and Heal (1994), however, have questioned the economists' typical presumption that marginal costs of abatement have to be identical for an pareto-efficient solution of the global climate problem. Using a static framework they showed: Provided, the global climate is viewed as public good, and provided neither capital nor carbon emission permits are traded on open international markets, identical marginal costs of abatement will be observed only if marginal utilities of income are equated across countries.

In our view, the assumption that there is no homogeneous commodity traded on an open international market is crucial for at least three reasons. First, if there is free international trade, then any tradable can play the role of a international numeraire. This, however, requires that the rates of return on capital are identical in all regions. For, if there were differences, then arbitrage and capital movements would equalize them almost immediately (see Manne and Rutherford, 1994).

Second, a no-free-trade assumption is in contrast to most of the regionally disaggregated impact models of global climate change. For example, in both RICE (see Nordhaus and Yang, 1996) and MERGE (see Manne and Richels, 1995), pareto-optimal abatement policies are achieved through “where” and “when” flexibility. That is, the abatement of greenhouse gases is determined in each region and in each time period by trading emission rights as homogeneous commodities on open international markets.

Finally, empirical evidence is inconsistent with a no-trade hypothesis as well as the fiction of a free-trade world economy. Recently, Gordon and Bovenberg (1996) have reconfirmed the findings of Feldstein and Horioka (1980) that capital is quite immobile internationally: On one hand, additional savings in one country will increase almost a dollar-for-dollar investment in just that country. On the other, there are regional differentials in real interest rates what provides further evidence of restrictions on international capital mobility.

Greenhouse gas abatement can be viewed as an alternative to conventional capital formation. Somehow, the society must agree on how to split its limited resources between investment in region-specific physical capital and global investment in environmental capital. Since restrictions on international trade in capital or in carbon emission rights can affect regional investment decisions, it might be expected that significant interregional differences in rates of return could affect global climate policy decisions. Analyzing this issue within the framework of a Computable General Equilibrium model is one of the aims of this paper.

A second issue is to answer the questions: What are the intertemporal effects of international capital market imperfection and/or restrictions on international trade in carbon emission rights on the global climate and regional welfare? Do constraints on "where to abate" flexibility affect marginal costs of abatement as well as marginal productivity of capital in the same way as restrictions on "where to invest" flexibility or in different ways? By this not only the Chichilnisky and Heal (1994) analysis is extended in several respects. A better understanding of the results from regional disaggregated impact models such as MERGE and RICE is also provided.

The rest of the paper is organized as follows: Section 2 discusses the main features of the modeling approach upon which the numerical analysis is based. Section 3 presents some analytical results, and Section 4 reports the outcome of the numerical calculations based on a conventional specification of data inputs. Section 5 obtains results for alternative parameter values. Concluding remarks are given in Section 6. Finally, a full description of the model can be found in the Appendix.

2. Theoretical framework

Since the purpose of our numerical thought experiments is insight and not numbers, the theoretical framework is kept deliberately simple. To relate our results to the existing literature, some of the basic ideas and numerical parameters from the RICE, MERGE and MEDEA (see Stephan and Müller-Fürstenberger, 1998) integrated assessment models are taken over into our stylized-facts model of the world economy.[1]

There are only two regions of the world. For vividness let them be called North (N) and South (S). North consists of the OECD countries including the former Soviet Union. South covers the rest of the world. Each region is represented as though it were an infinite-lived agent, maximizing the discounted utility of consumption over time (for a discussion, see Stephan and Müller-Fürstenberger, 1998). Both North and South employ identical utility discount rates, but South enjoys a higher rate of potential GDP growth than North. This immediately leads to the possibility of differential rates of return on capital between the two regions.

Time is taken as discrete and periods are one decade in length. Among the various greenhouse gases, carbon dioxide is considered as the most relevant one. Potential global warming is caused by increased atmospheric CO_2 concentration and directly affects production, but not utilities.

For each time period, there are just two tradable goods: the numeraire and carbon emission rights. The numeraire can be produced within each region and may be used for consumption, investment, net exports or carbon abatement. Carbon emission rights are assigned exogenously to each region through international negotiations, but these rights may be bought and sold so as to achieve economically efficient solutions.

[1] A complete list of the model equations can be found in the Appendix. The programming code is available from the authors upon request.

2.1 Climate-economy interaction

A "two-box" model is used to cumulate carbon emissions over time, and to translate them into global concentrations (for a detailed discussion, see Joos et al., 1999). The current stock of atmospheric carbon dioxide, Q(t), depends on the former one, Q(t-1), and past period global emissions, e(t-1):

(2.1) $$Q(t) = \Psi Q(t-1) + \Theta e(t-1).$$

Ψ is the factor by which natural abatement processes reduce existing stocks of atmospheric CO_2. Θ is the fraction of current global emissions that will accumulate in the atmosphere.

We neglect the thermal inertia lag between global carbon concentration and climate change. We also neglect the cooling effects of aerosols and the heating effects of greenhouse gases other than carbon dioxide. And we neglect climate externalities that are not valued in a market such as species loss for example. What we reflect, however, is that global climate change may affect productivity of different regions of the world in different ways.

Regional externalities of global climate change are represented by a quadratic concentration-damage function:

(2.2) $$\Phi^r(t) = 1 - [Q(t)/\Omega^r]^2.$$

The regional environmental loss factor $\Phi^r(t)$ indicates economic damages induced by global climate change in region r = N, S. The corresponding economic costs are measured in terms of forgone GDP. I.e., if the atmospheric carbon stock is raised to levels Q(t) above pre-industrial atmospheric carbon, then the productivity of factors is reduced in region r such that only $\Phi^r(t)$ percent of the region potential gross production are still available. Ω^r marks the critical value of atmospheric CO_2 perturbation at which production in region r = N, S is reduced to zero.

2.2 Production and greenhouse gas abatement

For convenience, let for each region r = N, S the conventionally measured gross output, $y^r(t)$, without climate effects be a Cobb-Douglas function

(2.3) $$y^r(t) = \beta^r L^r(t)^{\alpha(r)} K^r(t)^{1-\alpha(r)}$$

of regional labor $L^r(t)$ and capital $K^r(t)$ inputs, respectively. β^r is a scaling parameter and $\alpha(r)$ is the value share of labor.

As in RICE we sidestep a detailed energy sub-model by viewing carbon dioxide emissions as a linear function of total regional output. It is supposed that without greenhouse gas abatement, σ^r units carbon dioxide are emitted in region r, if one unit of conventional gross output is produced. Emissions can be reduced, however, by employing abatement activities. Therefore, region r's instantaneous carbon dioxide emissions, $e^r(t)$, are given by

(2.4) $$e^r(t) = (1 - a^r(t))\sigma^r y^r(t),$$

where $a^r(t)$ denotes the fraction of CO2 emissions abated in period t by region r.

This formulation allows to observe directly regional abatement costs $m^r(t)$. The latter are expressed in units of regional gross output and are supposed to be quadratic in abatement activities $a^r(t)$:

(2.5) $m^r(t) = \tau[a^r(t)]^2 y^r(t)$.

The scaling factor τ is chosen such that complete elimination of CO_2 emissions consumes twenty percent of the regional gross output. This is quite a pessimistic estimate. Suppose for example, that carbon-free backstop technologies were available at marginal costs of US$ 200 (see Stephan and Müller-Fürstenberger, 1998), then the scaling factor would be only 5 %. Our estimate is equivalent to average costs of 800$ US or marginal costs of 1400 $ US for carbon free energy.

2.3 International capital market imperfection

Climate change reduces the productivity of the regional economies (see (2.2)). Only the fraction $\Phi^r(t)$ of conventional gross output $y^r(t)$ is at the region's disposal. 'Green output' $\Phi^r(t)y^r(t)$ can be consumed, $c^r(t)$, invested into conventional capital formation, $i^r(t)$, or used for CO_2 abatement, $m^r(t)$. Regional output is considered as numeraire that can be traded international. Hence, if $x^r(t)$ denotes the net-exports of region r in period t,

(2.6) $\Phi^r(t)y^r(t) \geq c^r(t) + i^r(t) + m^r(t) + x^r(t)$

is the material balance of produced and tradable commodities in region r = N, S.

Restricted international mobility of capital as observed empirically might be associated with imperfect information transfers from one region to another. Alternatively, it could also be associated with prospective defaults on the repayment of debts (see Baxter and Jermann, 1997). In this paper we take the last view and consider limits on regional trade deficits as source for international immobility of capital (see Section 3).

2.4 Climate policy

There are two types of capital stocks, the society can control. In each region r the accumulation of the physical capital stock $K^r(t)$ follows a conventional rule

$$K^r(t+1) = (1-\upsilon^r)K^r(t) + i^r(t),$$

where υ^r is the region specific capital depreciation rate.

The environmental capital stock is determined by the atmospheric accumulation of carbon dioxide, hence depends upon the global climate policy. It is supposed that climate policy is the outcome of the cooperative solution of the greenhouse gas problem. By this, globally aggregated CO_2 emissions, e(t), are determined for each period. Carbon emission rights are assigned exogenously to each region through international negotiations.

$\xi^r(t)$ denotes the share of global emissions as assigned to region r in period t. This means, without trade in carbon rights, region r were allowed to consume $\xi^r(t)e(t)$ units of carbon dioxide during period t. With trade region r can either buy carbon emission rights or might sell a certain fraction of its endowment. Therefore, if $s^r(t)$ denotes net-exports of carbon emission rights, the right hand side of

(2.7) $e^r(t) \leq \xi^r(t)\, e(t) - s^r(t)$

sets an upper bound on CO_2 emissions of region r in period t.

Given the characterization of the theoretical approach so far, the most simple way to look at the economics of global climate change is to suppose that regions follow a Ramsey path. I.e., if δ is the social discount factor, then consumption, production, investment into physical capital and greenhouse gas abatement are determined in each region r =N, S, as if a policy maker has maximized the discounted sum of the logarithm of consumption $c^r(t)$

(2.8) $$W^r = \Sigma_t \delta^{-t} \ln(c^r(t))$$

for striking an optimal balance between consumption and physical investment.

To close the model, two additional conditions have to be added for each period t.

(2.9) $$x^N (t) + x^S (t) = 0$$

is trade balance for trades in the numeraire.

(2.10) $$s^N (t) + s^S (t) = 0$$

says that globally exports and imports of carbon rights have to be in balance.

3. Analytical considerations

In the following we show analytically that marginal costs of abatement differ across regions, if international capital markets are imperfect.

Marginal costs of abatement, $mca^r(t)$, can be calculated from (2.4) and (2.5). This immediately implies

$$-\partial m^r(t)/\partial e^r(t) = -[\partial m^r(t)/\partial a^r(t)][\partial a^r(t)/\partial e^r(t)],$$

hence

(3.1) $$mca^r(t) = 2a^r(t)\tau/\sigma^r.$$

Let $p^N(t)$ and $q^N(t)$ the prices of produced outputs and carbon emission rights, respectively, that prevail in the northern hemisphere. Then first order conditions yield (see (2.6) and (2.7))

(3.2) $$p^N(t)\ mca^N(t) = q^N(t),$$

Furthermore, since trade in carbon emission rights as well as in the numeraire have to be in balance globally (see (2.9) and (2.10)), we obtain

$$q^N(t) = q^*(t) \quad \text{and} \quad p^N(t) = p^*(t).$$

$q^*(t)$ and $p^*(t)$ are the world market prices of carbon rights and the numeraire, respectively. Hence, domestic and international prices of the numeraire and carbon coincide, and marginal costs of abatement must equal the real price of carbon permits:

(3.3) $$mca^N(t) = q^*(t)/p^*(t).$$

Now, if there are no limits on international capital mobility, the consideration from above can be repeated for the South. Consequently, without market imperfection, marginal costs of abatement have to be identical in both regions.

But what, if international capital markets are imperfect? What, if the South faces a constraint on trade deficits that limits its ability to import foreign capital, as discussed in Section 2.3? Formally, limits on southern trade deficits are given through

(3.4) $$\Gamma(t)p^*(t)[\Phi^S(t)y^S(t) - m^S(t)] \geq [p^*(t)x^S(t) + q^*(t)s^S(t)].$$

$\Gamma(t)$ is the maximum value-ratio of debt financed net-imports to domestic output (less abatement costs). $p^*(t)$ and $q^*(t)$ are as above the world market prices of the numeraire and carbon permits, respectively.

Exporting carbon permits to the North will yield revenues which can be used to finance additional imports of the numeraire. Through taking derivatives of (2.7), (2.10), and (3.4) with respect to carbon exports, $s^S(t)$, first order optimality conditions imply

(3.5) $$q^S(t) = (1 + \nu(t))q^*(t),$$

where $\nu(t)$ is the shadow price of the debt constraint (3.4). Hence, domestic prices of carbon are above international carbon prices as long as the debt constraint is binding. One might guess, therefore, that marginal costs of abatement should be higher in South than in North.

However, this is wrong. Marginal costs of abatement are valued in domestic terms of the numeraire. To see this, consider the first order conditions after differentiating (2.6), (2.9) and (3.4) with respect to net-exports, $x^S(t)$, of the numeraire. This immediately shows that domestic and international prices interrelated

(3.6) $$p^S(t) = (1 + \nu(t))p^*(t).$$

In other words, both regions face the same real price of carbon permits. Debt-relaxation drives no wedge between marginal costs of abatement.

Exporting carbon permits, however, has a second effect on the debt constraint. Since abatement absorbs gross production, it tightens the debt constraint. Thus selling carbon permits not only increases domestic abatement costs but also reduces South's debt capacity. To pin down this effect, (2.6), (2.7), and (3.4) are differentiated with respect to carbon emissions $e^S(t)$:

(3.7) $$mca^S(t)\, p^*(t)\, [1 + \nu(t)\, \Gamma(t)] = q^*(t).$$

The second term in brackets reflects the effect just described above. From (3.3) and (3.7) we obtain

(3.8) $$mca^S(t) < mca^N(t),$$

which provides the theoretical underpinning of our result in Section 4.

4. Numerical results

4.1 Scenarios

Basically, there are two different ways to look at the global climate problem (see Stephan and Müller-Fürstenberger, 1998). One option is to take a descriptive view and relate the global climate problem to principles of economic efficiency. This means, the climate problem is placed into the framework of a decentralized market economy. Efficient greenhouse gas abatement policies are identified through cost-benefit considerations where the market rate of interest is used for evaluating investments both in physical and environmental capital.

Alternatively, one could take a prescriptive approach and relate the global climate problem to ideas of intergenerational fairness and equity. Current emissions are small compared to the existing stock of atmospheric carbon. Hence, abatement costs are born early and benefits do not accrue until the distant future. The lower the rate of discounting, the higher is the weight placed upon the well-being of the future generations. It is no surprise therefore that intergenerational equity calls for discounting the future climate at rates that are significantly below the market rate of interest.

Just as in the related literature we take a descriptive view and base our main results the assumption that future utilities are discounted at a rate of 3%. This roughly corresponds to discounting at the market rate of interest. Since we expect, however, that the discount rate will affect the numerical simulations, results are also reported for a prescriptive approach, where future utilities are discounted at a rate of 1%. Furthermore, calculations are designed so that there could be a substantial reduction of today's North-South per capita income disparities during the next century. This is why we suppose that without greenhouse policy North will have an average annual GDP growth rate of 1.5% and South will grow at a rate of 3.5%.

Given the model formulation (see (2.8)) both regions follow a Ramsey path for striking an optimal balance between consumption and physical investment. If there were no capital mobility and no investment in greenhouse gas abatement, both regions would develop independently. Along an optimal growth path, there could be a 4.5% rate of return on capital in the North and 6.5% in the South.

But what if the regions agree to cooperate on greenhouse abatement, and what if there are limited options for capital flows? We examine the outcome - assuming that prices, supplies and demands are generated through a multi-period general equilibrium model. Solutions are obtained via Rutherford’s sequential joint maximization method - a specialization of the Negishi approach (see Rutherford 1995).

Based on these considerations, four policy scenarios are identified (see Table 1):

Policy scenario	CMCT	CMCNT	CRCT	CRCNT
Full capital mobility	X	X		
International trade of carbon rights	X		X	

Table 1: Classification of policy scenarios

CMCT denotes the scenario with greatest flexibility. There is full international capital mobility, and carbon emission rights are traded on open international markets. CRCT means that there are limits on international capital flows but free trade of carbon rights. Unrestricted capital mobility, but no trade in carbon emission rights at all is identified by CMCNT. Finally, CRCNT represents the scenario with lowest flexibility. There are restrictions on international capital mobility and there is no international trade of carbon emission rights. If necessary regional effects are identified by adding either N (North) or S (South) in brackets.

4.2 Market imperfection and the global climate

Trading both capital and carbon emission rights on open international markets increases the world's "where to abate" as well as "where to invest" flexibility. Without trade restrictions, scarce resources, capital and abatement activities can be allocated more efficiently. Consequently, low-cost abatement facilities might be used more extensively, and conventional output should be higher. However, although the world can be richer in terms of conventional welfare, it might get purer in environmental quality. Growth in GDP correlates with higher carbon emissions (see (2.4)). And it is not clear a priory that the resulting climate effect is compensated by extending low-cost abatement.

As Figure 1 indicates "where to abate" and "where to invest" flexibility affects the global climate in quite different ways. Limits on "where to invest" flexibility have only negligible effects on atmospheric carbon concentration. If the future climate is discounted at the market rate of interest, then, just as Manne and Stephan (1999) have reported, an invariance result is observed. The stock of atmospheric carbon dioxide is virtually independent of the degree of international capital mobility.

This is quite in contrast to the result we observe if we compare global climate policies with or without trade in carbon emission rights. As Figure 1 demonstrates, no trade in carbon emission rights is a better alternative from an ecological perspective. At the global level it causes lower carbon dioxide emissions. This can be explained by two negative effects, a low "where to abate" flexibility has on regional GDP. First, the North now must fully reduce carbon emissions even at high costs (see Figure 2). Second, South cannot finance expansion of its capital stock by selling carbon permits.

Indeed, without international trade in carbon rights, greenhouse gas abatement is inefficiently allocated. As Figure 3 shows, marginal costs of abatement are then always higher in North than in the South. This corresponds to high abatement activities in the North, and almost none in the South (see Figure 2 and Figure 2a). On the other hand, if there were full "where to abate" flexibility, then through buying emission rights, North can expand its CO_2 emissions at relative low cost. This is reported by Figure 2, which shows that abatement activity in North declines dramatically in case of carbon trade. Therefore, high "where to abate" flexibility directly correlates to low carbon abatement activities in the North. Coinciding, the South can generate income through selling carbon emission permits which allows to finance capital imports. This creates welfare gains in both regions but leads to a higher atmospheric carbon concentration (again see Figure 1).

Obviously, this result is very much driven by the initial distribution of carbon rights. If the South has a high initial endowment (75%) of carbon emission rights, then without trading carbon rights on open international markets its optimal strategy will be not to abate at all for almost one century. Changing the distribution of carbon rights in favor of North narrows the gap between marginal costs of abatement in these two regions. The basic pattern, however, is still observed.

4.3 Market imperfection and regional economies

Theory predicts (see Section 3) that in the case of capital market imperfection marginal abatement costs are higher in the North than in the South. However, numerically these effects are hardly to be recognized at all. What really seems to matter and visually drives the results is whether there is trade in carbon emission rights or not. Compared to that the effects of restrictions on international capital mobility on global climate are almost negligible. Just the opposite is observed, however, if the impact of trade restrictions on marginal productivity of capital and per capita consumption are considered (see Figure 4 and Figures 5 and 5a).

As might be predicted from the model formulation (2.6), differences in regional marginal productivity of capital will diminish if the international mobility of capital increases. Just this outcome is observed in Figure 4. Figure 4 also shows that the marginal productivity of capital is independent of the degree of "where to abate" flexibility, at least if the international capital markets are perfect.

If capital markets are perfect, then marginal productivity of capital is identical for both regions. Nevertheless, "where-to-abate" flexibility can have some impact on the marginal productivity of capital. Trading carbon emission rights on open international markets reduces marginal productivity. An explanation for this observation is given through Figures 1, 2, and 2a. With carbon trade due to reduced abatement in North that is not fully compensated through additional abatement in South global emissions are higher. In other words, the North substitutes conventional capital for abatement activity. As a result, the marginal productivity of capital declines.

In a highly stylized model as the one presented here per-capita consumption is a reasonable proxy for welfare. As easily can be recognized from Figure 5, a policy regime that would provide both "where to abate" and "where to invest" flexibility were most favorable to the North. The worst possible outcome, the North might be confronted with, is observed in the (CRCNT) scenario which roughly represents the present state of international climate policy: no international trade in carbon emission rights on one hand and capital market incompleteness on the other . In fact, the (CRCNT) path is dominated by the full flexibility (CMCT) scenario over the whole time period.

Per-capita consumption in South (Figure 5a) does not reveal a clear "worst-case". Free trade both in capital and in carbon emission rights improves welfare in terms of per capita-consumption, but only in the short term. This is mainly due to capital imports which boost domestic production. But since these imports are financed by debt, repayment drives down domestic consumption afterwards. Therefore, in the very long-run, no flexibility at all proves optimal to the South.

5. Sensitivity analysis

5.1 Sensitivity with respect to the discount rate

Let us now take a different view of the world. Let us assume that the future is discounted at 1% which is significantly below the market rate of interest. Will the invariance result still be observed which says that capital market imperfection visually does not affect marginal costs of abatement and the atmospheric accumulation of carbon?

Obviously, the answer is no. As can be seen from Figure 6, capital market imperfection now has an impact on global climate. The growth-dumping effect of capital market imperfection causes lower emissions and implies lower stocks of atmospheric carbon. And if we compare Figure 1 and Figure 6, two further effects can be identified. First, a lower utility discount rate leads to higher investment into environmental capital. In general carbon accumulation is now remarkable slowed down compared to discounting at the market rate. Second, with respect to "where-to-abate" flexibility, in principle same patterns as with 3% utility discounting are observed.

Finally, regional per-capita consumption is shown in Figures 7 and 7a. With a low discount rate more capital is exported from the North to the South. This explains why - in contrast to the 3% case - North now experiences significant losses in per capita consumption at the beginning of the time horizon, if there are no limits on international capita mobility. South gains from these capital imports relative to the case without "where-to-invest" flexibility. However, from the middle of the century onwards repayment of debt renders a free trade scenario inferior to a restricted trade one.

5.2 Sensitivity with respect to other parameters

We find invariance when several of the key parameters are altered. Two examples are shown, but others may easily be generated. There is PBAK, a case in which the cost of the futuristic carbon-free backstop technology increase such that complete abatement of carbon would consume 30 % of GDP instead of 20%. And there is CLOME, a case in which the economic costs of climate damages are doubled.

Both these variants lead to significant near-term declines in the absolute value of global emissions, but did not reveal significant differences in sensitivity among our "where-to-abate" and "where-to-invest" scenarios. Just for illustrative purposes, we confine ourselves to impacts on atmospheric carbon.

Differences in atmospheric carbon relative to our baseline scenario are shown in Figure 8. Doubling climate damages initiates more abatement, and by the end of the century carbon stocks are about 10% below those in the base case. "Where-to-abate" flexibility affects global climate only slightly. With free carbon trade, doubling climate damages has a greater impact on atmospheric carbon than without trade.

Higher abatement costs should negatively affect on abatement activities, thus must lead to atmospheric carbon concentration. Figure 8 shows, that peak levels at 2100 are 5 % above those within in our baseline assumption. However, differences according to trade restrictions are not recognized.

6. Concluding remarks

When we began this study, based on conventional wisdom we anticipated at least three effects, restriction on international "where-to-abate" and "where-to-invest" flexibility should have on the economically efficient rate of global decarbonization, marginal costs of abatement, rates of return on capital, as well as on economic welfare.

Our first hypothesis was that capital market imperfection causes different marginal costs of abatement and different returns on capital across regions. By way of computational experiments and analytical reasoning, this turned out to be true. Capital market imperfection spills over to abatement costs. However, differences become only obvious if the world is viewed from a prescriptive perspective. If the future is discounted at the market rate, then the marginal rates of abatement are virtually independent of the degree of international capital market imperfection.

A second hypothesis claimed that lowering the discount rate amplifies the impacts of capital market imperfections. Again, this turned out to be true. In case of marginal costs of abatement, differences across regions occur only in case of low discount rates. We also observed differences in carbon accumulation according to whether where-to-invest applies or not. That is, invariance result of Manne and Stephan (1999) does not survive large deviations from discounting at market rates.

Finally, we expected that significant trade restrictions have an impact on economic growth and greenhouse policy. With respect to consumption, trade restrictions provide welfare losses mostly to North. Impacts on South’s consumption patterns are more complicated. There, trade restrictions harm current generations but improve future generations welfare. The resulting conflict between North and South will be subject to future research.

REFERENCES

Baxter, M. and Jermann, U.J. (1997), “The International Diversification Puzzle is Worse Than You Think”, *American Economic Review* 87:170-180.

Chichilnisky, G. and Heal, G. (1994), “Who should abate carbon emissions? An international viewpoint“, *Economic Letters* 44:443-449.

Feldstein, M. and Horioka, C. (1980), “Domestic Saving and International Capital Flows”, *Economic Journal* 90: 314-329.

Gordon, R.H. and Bovenberg, A.L. (1996),“ Why is Capital so Immobile Internationally? Possible Explanations and Implications for Capital Income Taxation“, *American Economic Review* 86:1057-1075.

Joos, F., Müller-Fürstenberger, G. and Stephan, G. (1999), "Correcting the carbon cycle representation: How important is it for the economics of climate change", *Environmental Modelling and Assesment* 4:133-140.

Manne, A.S. and Rutherford, T.F. (1994), “International Trade, Capital Flows and Sectoral Analysis”, pp. 191-205 in W.W. Cooper and A.B. Whinston (eds.), *New Directions in Computational Economics*, Kluwer Academic Publishers, Netherlands, 1994.

Manne, A.S. and Richels, R.G. (1995), “The Greenhouse Debate, Economic Efficiency, Burden Sharing and Hedging Strategies”, *The Energy Journal* 16:1-37.

Manne, A.S and Stephan, G. (1999), “Climate change policies and international rate-of-return differentials“, *Energy Policy* 27:309.-316.

Nordhaus, W.D. and Yang, Z. (1996), “A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies”, *American Economic Review* 86:741-765.

Rutherford, T.F. (1995), “Sequential Joint Maximization”, working paper, University of Colorado, Boulder, 1995.

Stephan, G. and Mueller-Fuerstenberger, G. (1998), “Discounting and the Economic Costs of Altruism in Greenhouse Gas Abatement”, *Kyklos* 51:321-338.

Weyant, J. (1997), “Preliminary Results from EMF 14 on Integrated Assessment of Global Climate Change”, *Energy Modeling Forum Occasional Paper 14.1*, Stanford University, Stanford, 1997.

Appendix: Algebraic representation of the model

This Appendix provides a complete listing of model variables, parameters, and equations. Lagrange-multiplieres are attached in brackets to some of the equations.

Variables and Parameters

$y^r(t)$	Regional output (GDP)
$L^r(t)$	Labor input
$K^r(t)$	Capital input
$\Phi^r(t)$	Green capital factor ($0 \le \Phi^r(t) \le 1$)
$c^r(t)$	Consumption
$i^r(t)$	Investment
$M^r(t)$	Abatement costs
$x^r(t)$	Exports of GDP
$s^r(t)$	Exports of carbon permits
$a^r(t)$	Abatement activity ($0 \le a^r(t) \le 1$)
$p^r(t)$	Domestic price of GDP
$p^*(t)$	World market price of GDP
$q^r(t)$	Domestic price of carbon permits
$q^*(t)$	World market price of carbon permits
$Q(t)$	Atmospheric carbon
$e^r(t)$	Regional carbon emissions
$e(t)$	World carbon emissions
$m^r(t)$	Abatement costs
$K^r(t)$	Capital stock
$\nu(t)$	Shadow price of the debt constraint
$\alpha(r)$	Labor value share
β^r	Production scaling
lg^r	Labor growth rate
υ^r	Capital survival rate
Ψ	Long-run decay of atmospheric carbon
Θ	Immediate oceanic uptake of atmospheric carbon
Ω^r	Critical carbon concentration
$\xi^r(t)$	Initial share in carbon permits
σ^r	Emission coefficient
τ	Abatement cost coefficient
$\Gamma(t)$	Limit on trade deficit
δ	Utlitiy discount rate

Equations

Gross production

(A.1) $$y^r(t) = \beta^r L^r(t)^{\alpha(r)} K^r(t)^{1-\alpha(r)}$$

Material balance

(A.2) $$\Phi^r(t) y^r(t) \ge c^r(t) + i^r(t) + m^r(t) + x^r(t) \qquad [p^r(t)]$$

Labor constraint

(A.3) $L^r(t) \leq (lg^r)^t L^r(0)$

Capital accumulation

(A.4) $K^r(t+1) = \upsilon^r K^r(t) + i^r(t)$

Carbon accumulation

(A.5) $Q(t) = \Psi Q(t-1) + \Theta e(t-1)$

Green capital factor

(A.6) $\Phi^r(t) = 1 - [Q(t)/\Omega^r]^2$

Regional carbon constraint

(A.7) $e^r(t) \leq \xi^r(t)\, e(t) - s^r(t)$ $[q^r(t)]$

Regional carbon emissions

(A.8) $e^r(t) = \sigma^r y^r(t)[1- a^r(t)]$

Abatement costs

(A.9) $m^r(t) = \tau[a^r(t)]^2 y^r(t)$

Trade balance for the numeraire

(A.10) $x^N(t) + x^S(t) = 0$ $[p^*(t)]$

Trade balance for carbon rights

(A.11) $s^N(t) + s^S(t) = 0$ $[q^*(t)]$

Debt constraint for South

(A.12) $\Gamma(t)\, p^*(t)[\Phi^r(t) y^S(t) – m^S(t)] \geq -[p^*(t) x^S(t) + q^*(t) s^S(t)]$ $[\nu(t)]$

Regional welfare function

(A.13) $W^r = \Sigma_t\, \delta^{-t} \ln(c^r(t))$.

Figure 1: Atmospheric carbon

3 % utility discounting

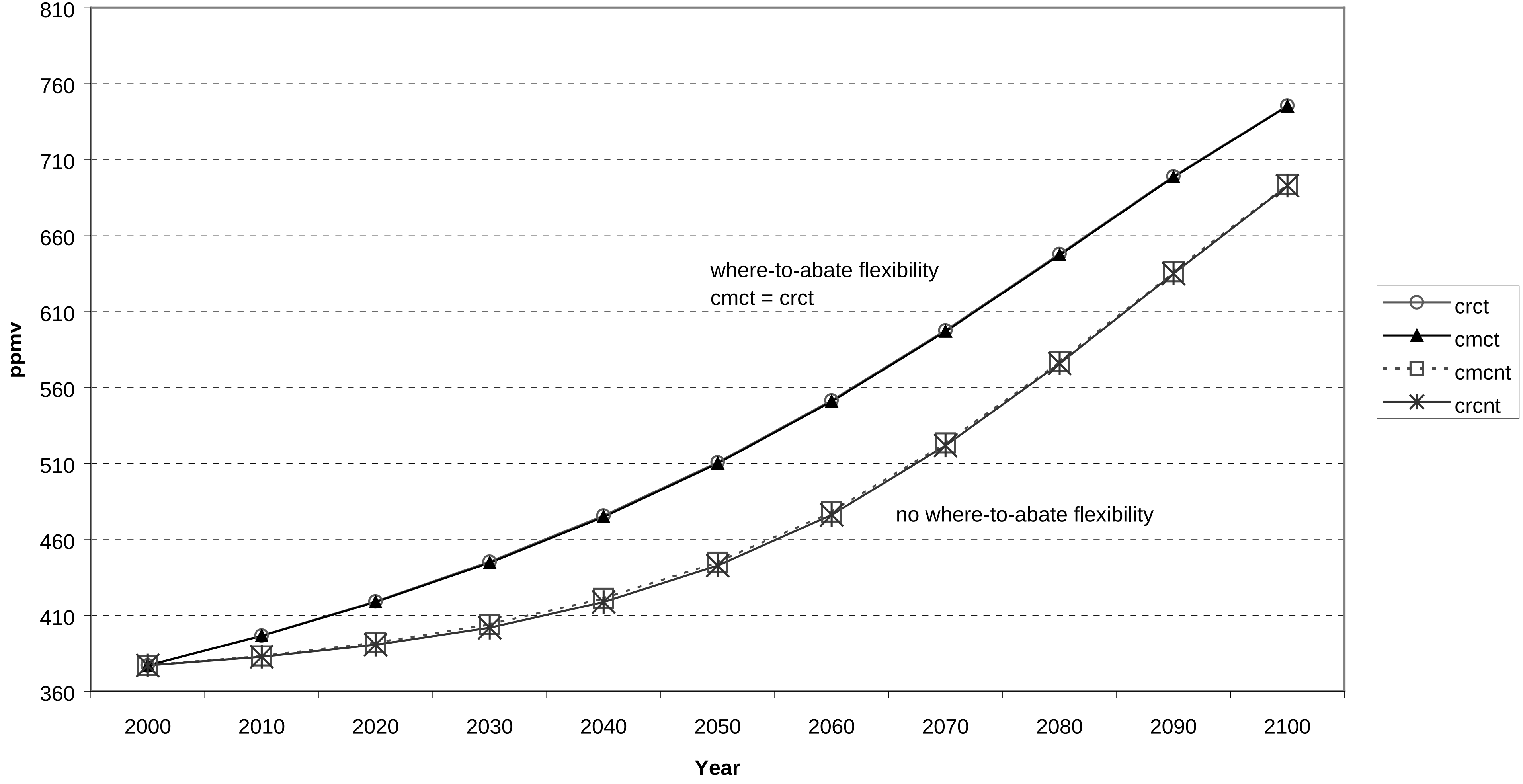


Figure 2: Abatement activity

North, 3 % utility discounting

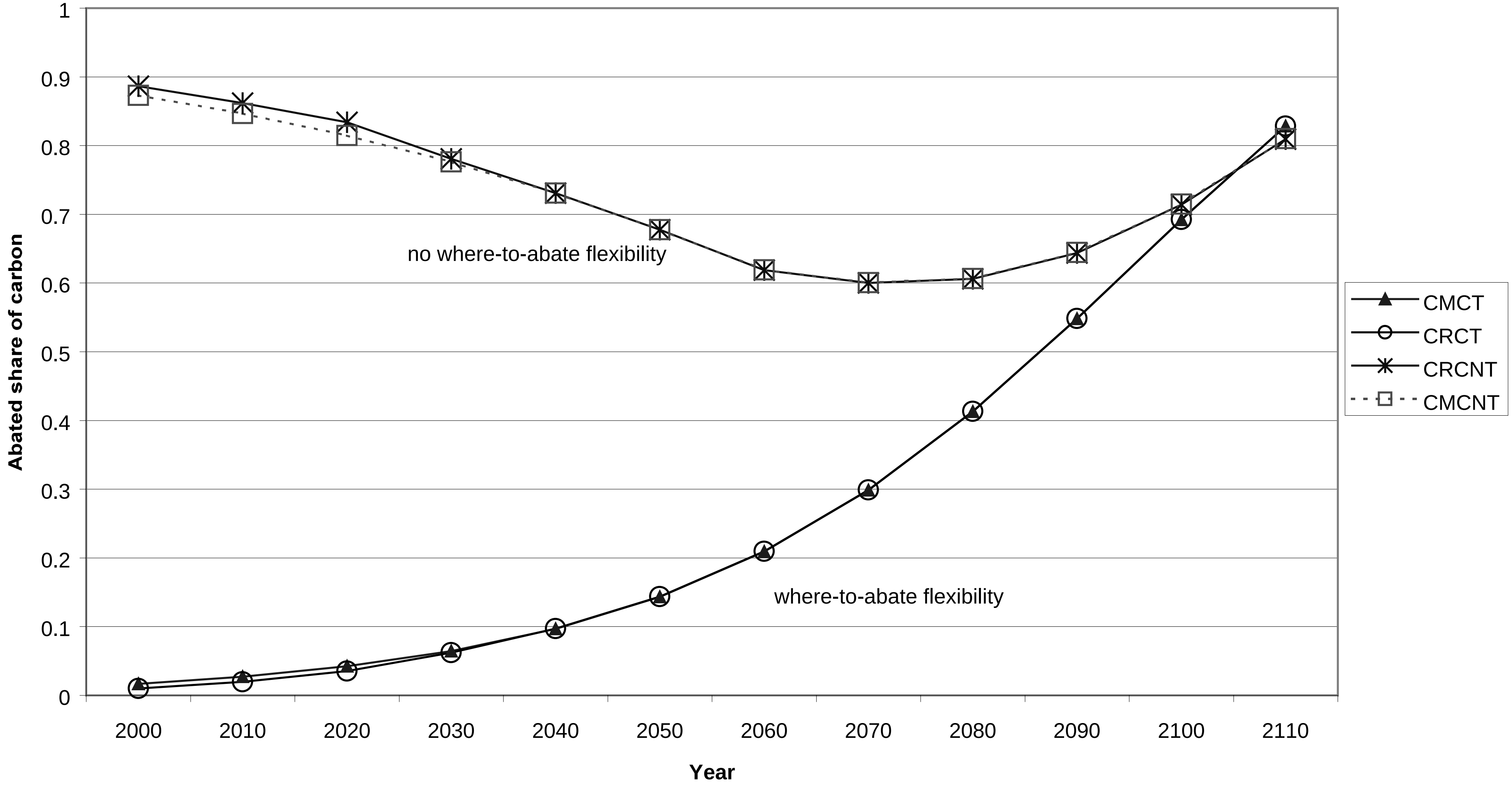


Figure 2a: Abatement activity

South, 3 % utility discounting

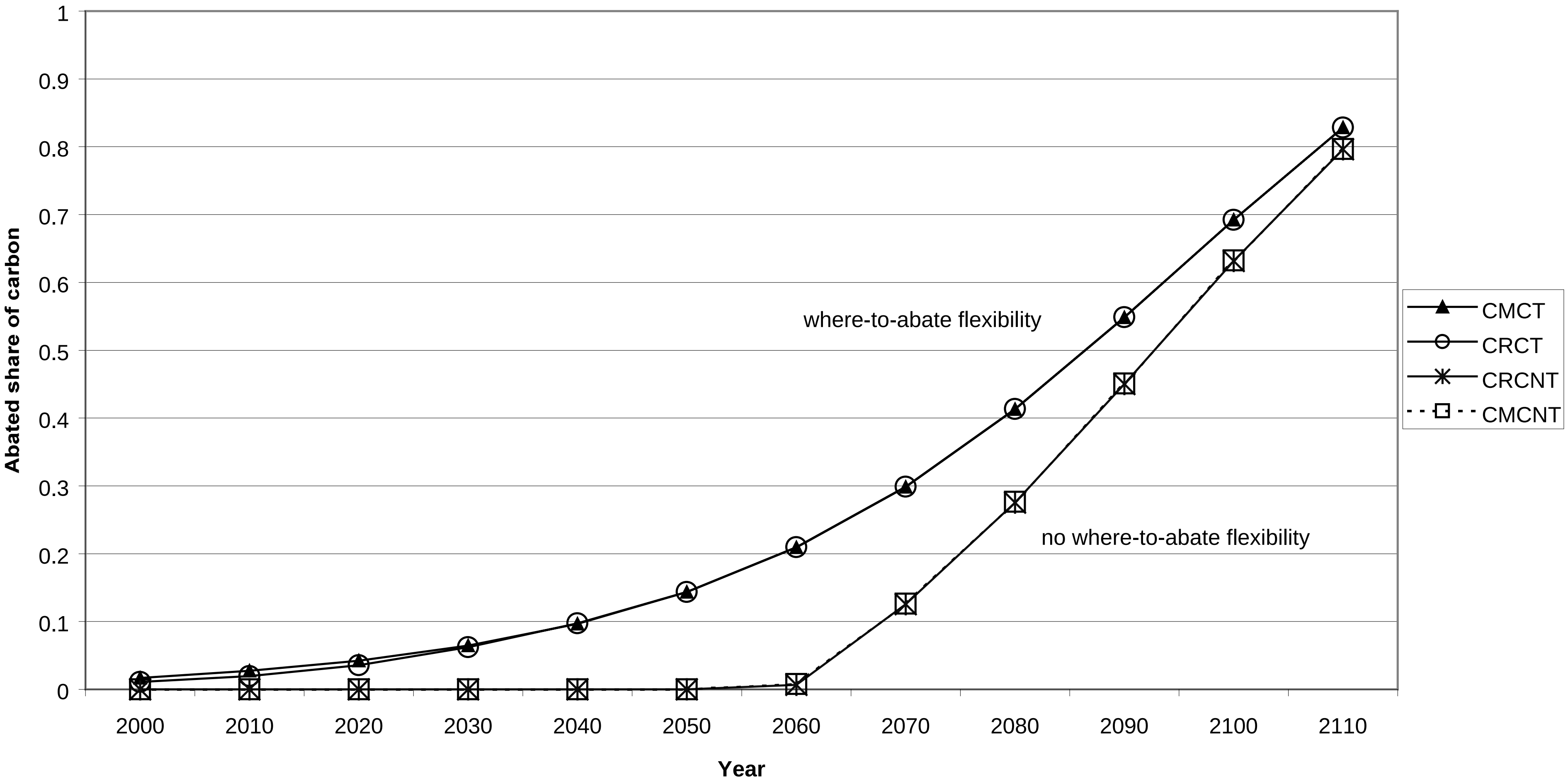


Figure 3: Marginal Cost of Abatement

3 % utility discounting

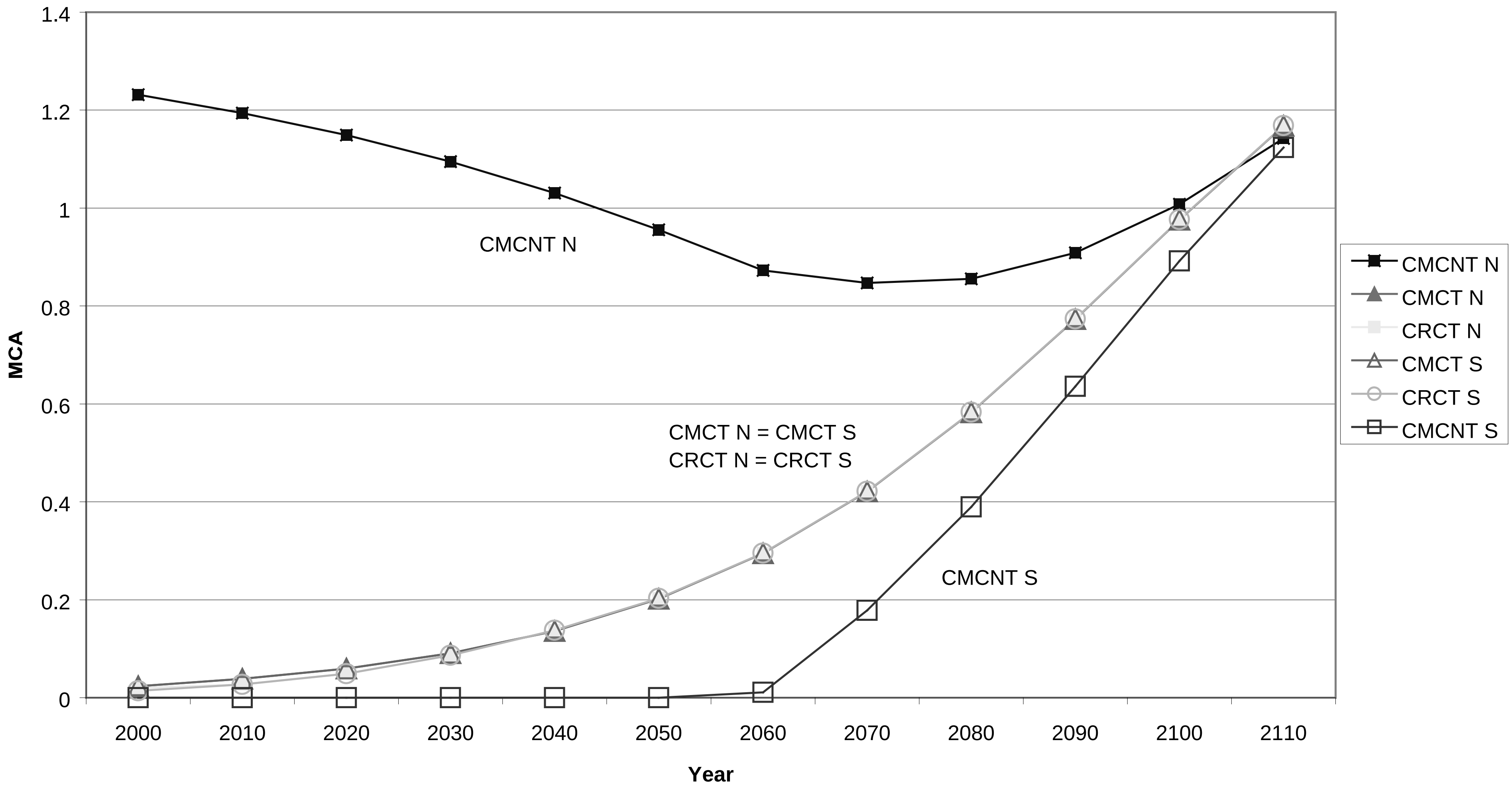


Figure 4: Marginal productivity of capital

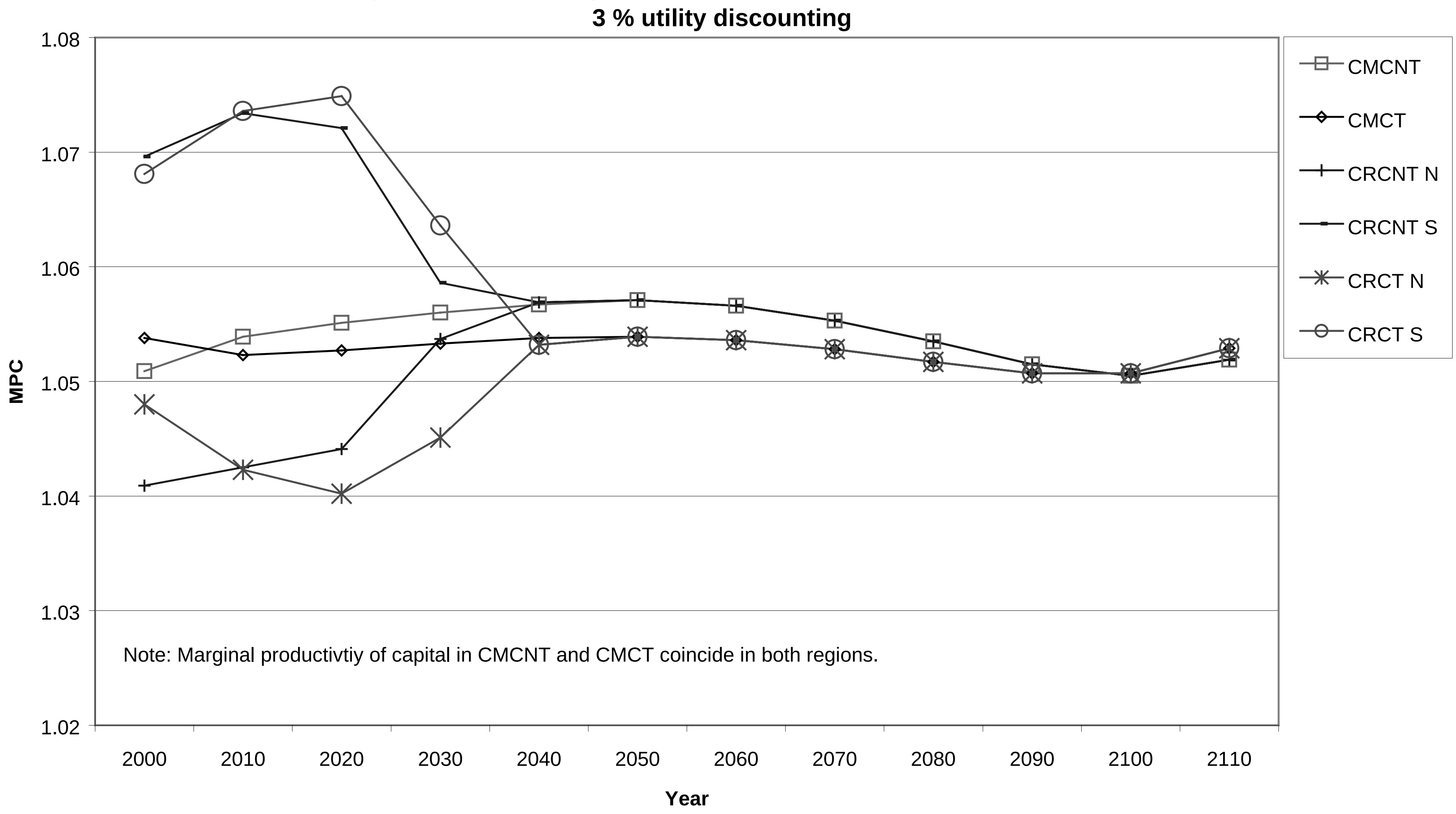


Figure 5: Consum

North, constant population, 3 % utility discounting

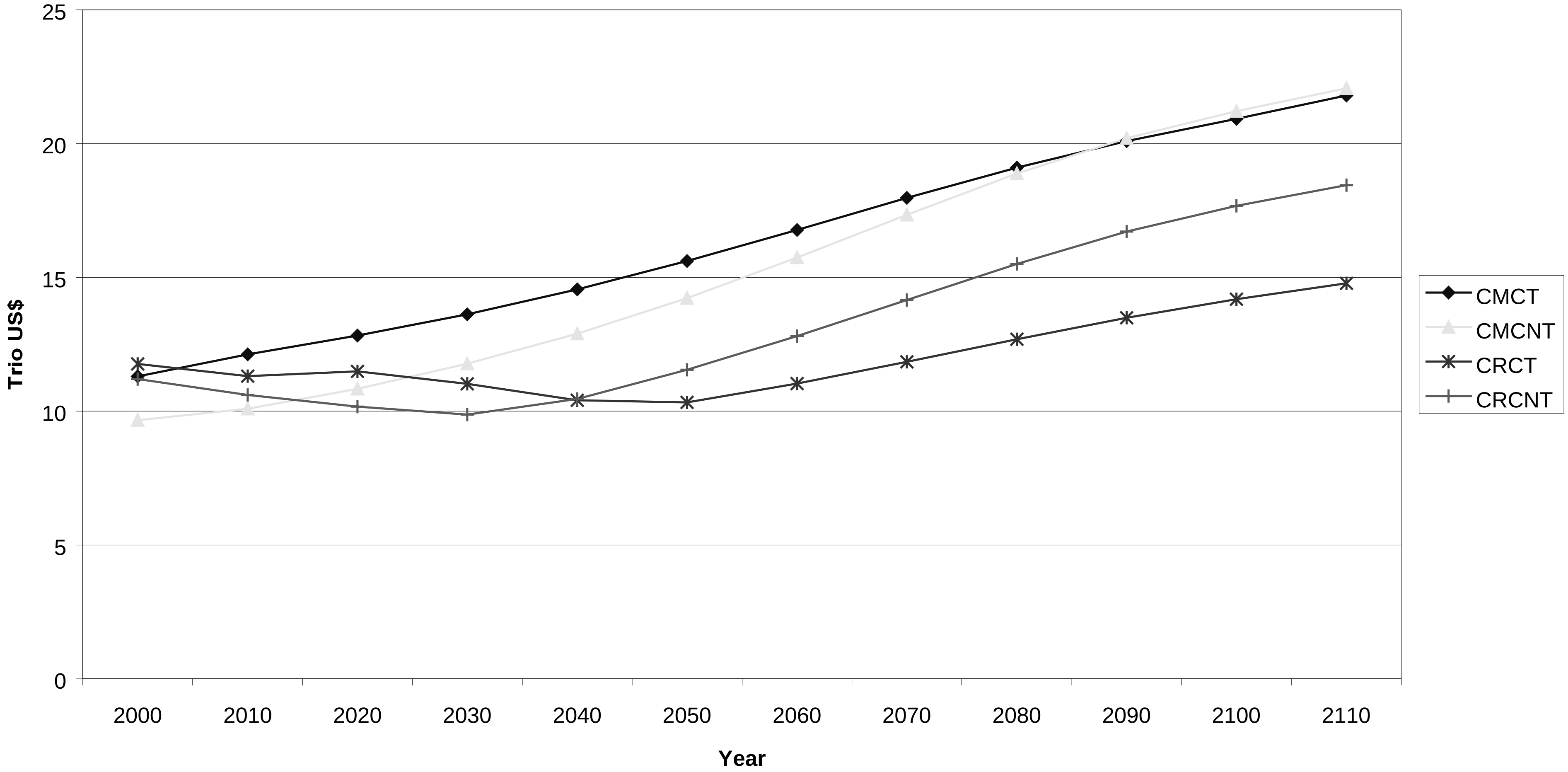


Figure 5a: Consum

South, constant population, 3 % utility discounting

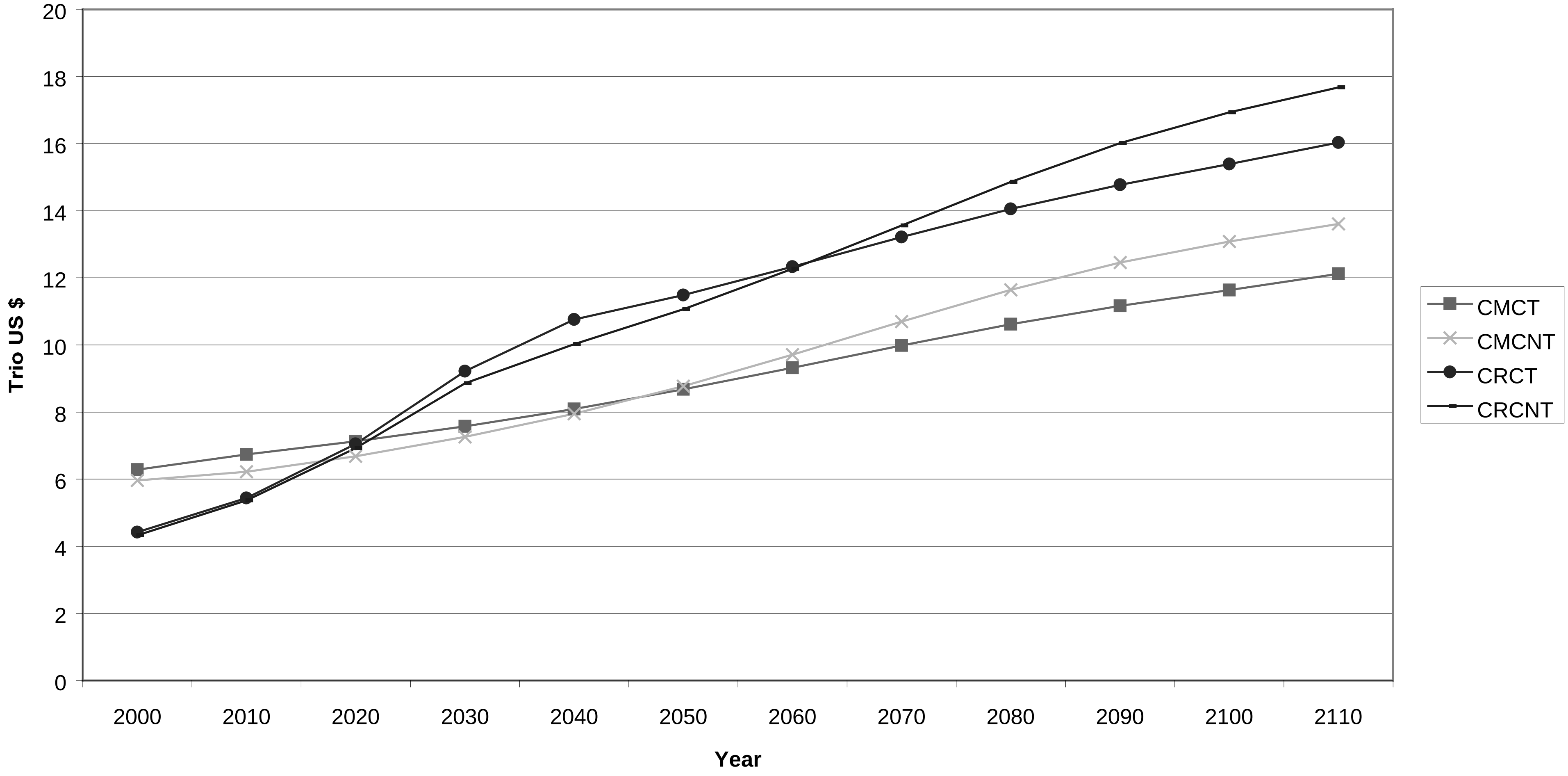
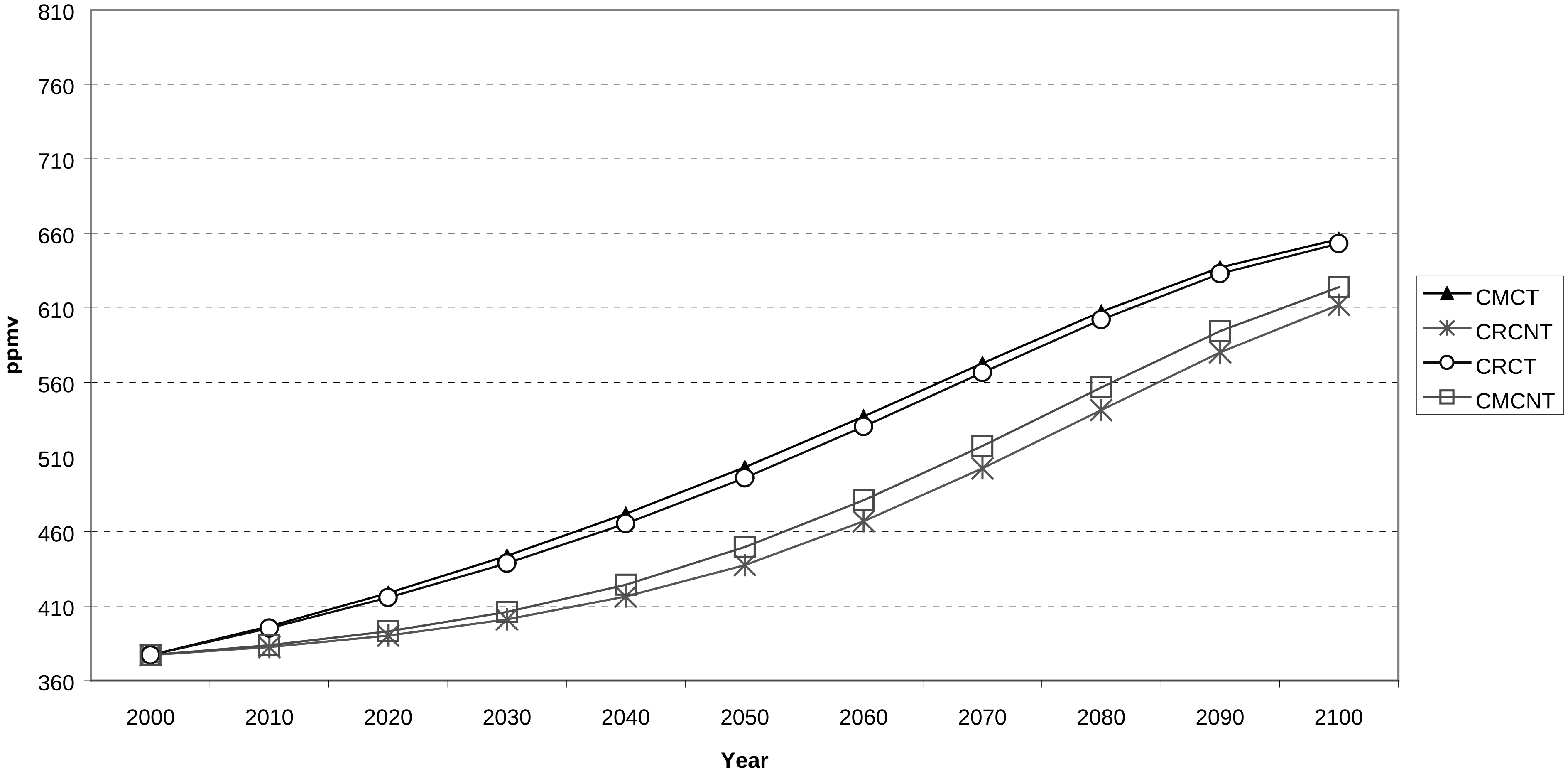


Figure 6: Atmospheric carbon

1 % utility discounting



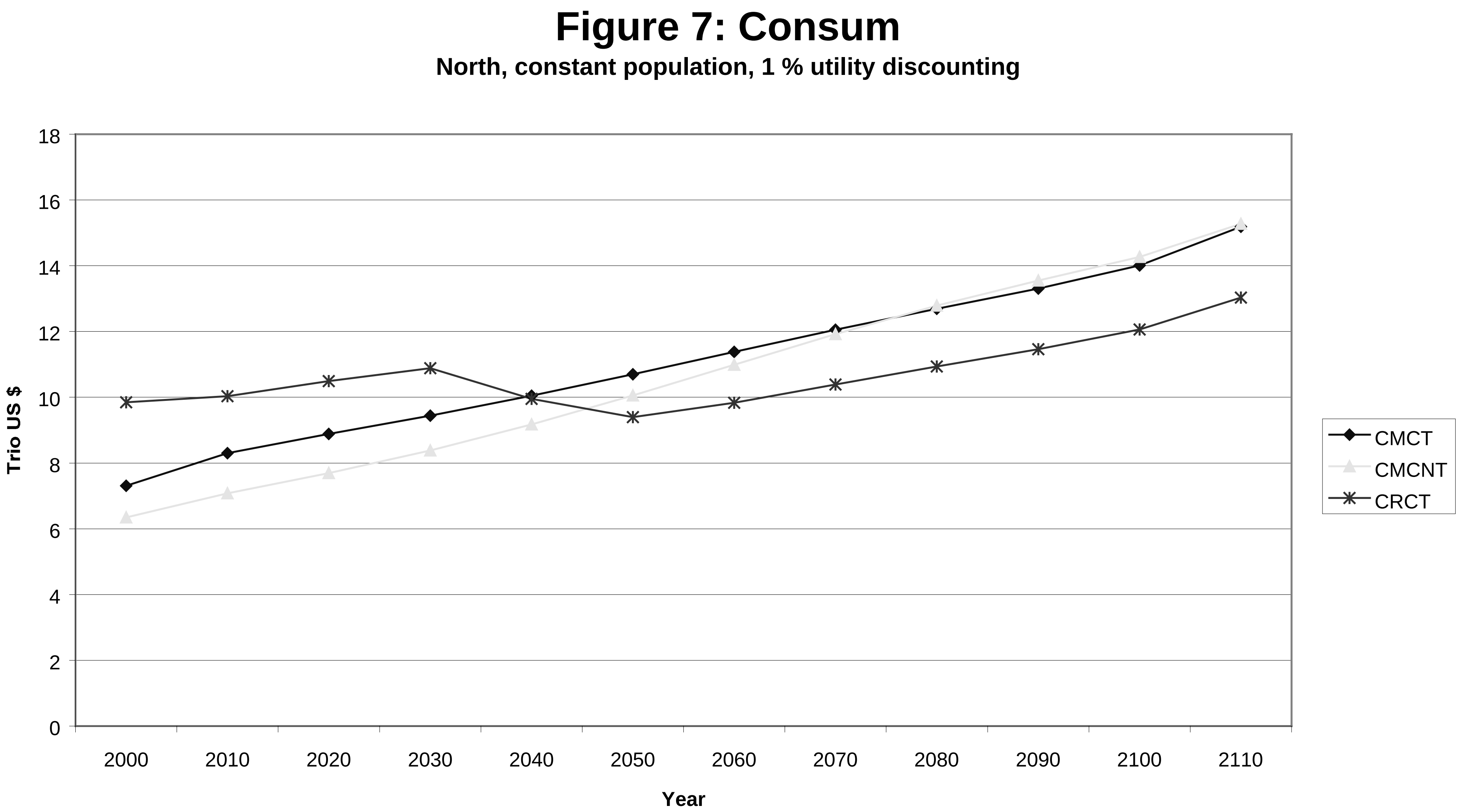


Figure 7: Consum
North, constant population, 1 % utility discounting
Trio US $
18
16
14
12
10
8
6
4
2
0
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2110
Year
CMCT
CMCNT
CRCT

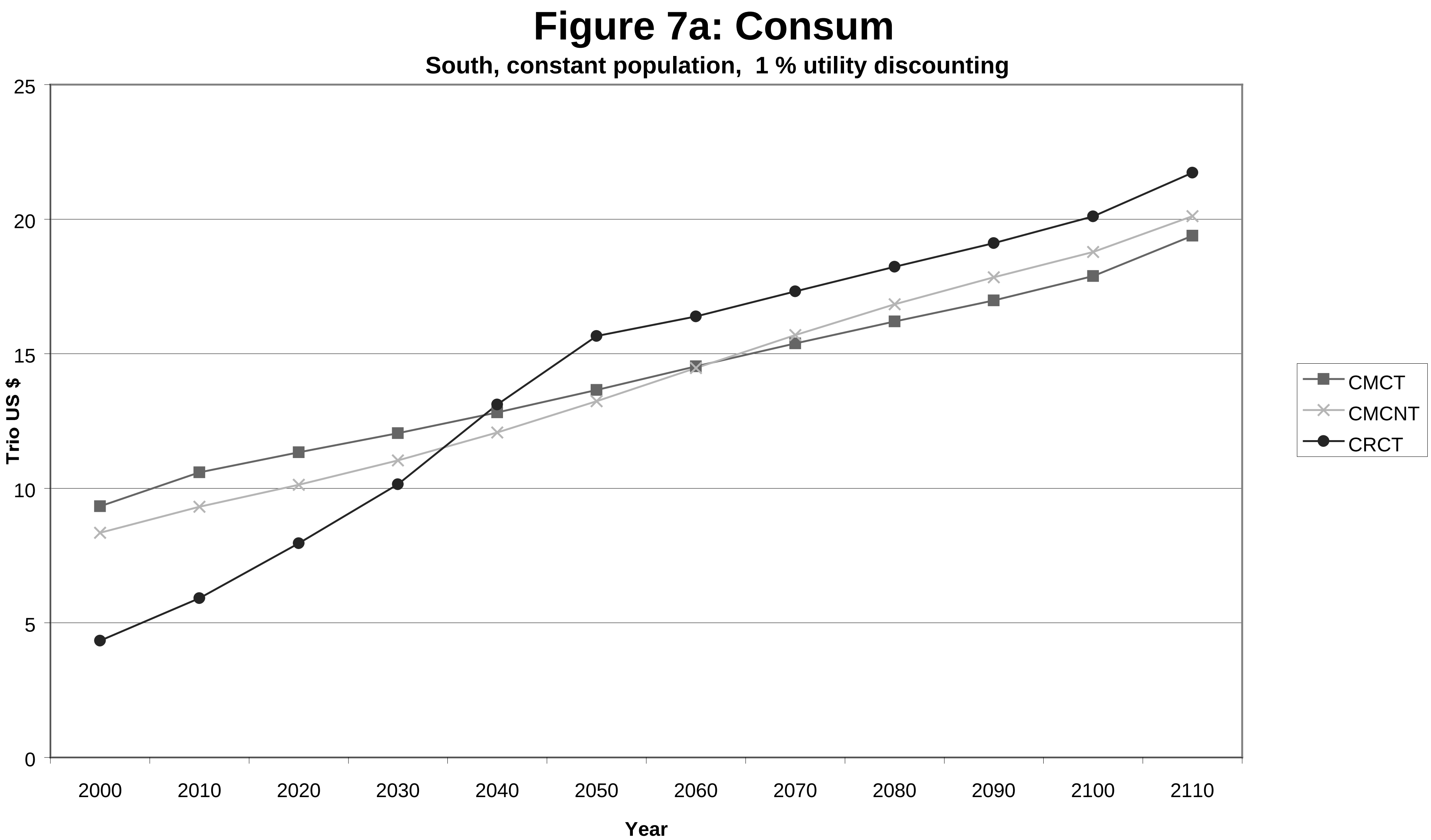


Figure 7a: Consum
South, constant population, 1 % utility discounting
Trio US $
Year
CMCT
CMCNT
CRCT
0
5
10
15
20
25
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
2110

Figure 8: Sensitivity of Atmospheric Carbon

3 % utility discounting