OVERLAPPING GENERATIONS VERSUS INFINITELY-LIVED AGENT THE CASE OF GLOBAL WARMING

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ABSTRACT

This chapter demonstrates that results from climate change models using the OLG approach can depend significantly on various economic and social conditions. Thereby, policy recommendations derived from OLG models can prove rather different from those resulting from conventional ILA models. This chapter presents the integrated assessment OLG model for the analysis of global warming ALICE 1.2, which allows for modeling a flexible interest rate and for incorporating various assumptions on demographic change and public institutions designed for the protection of the environment. Thus, ALICE 1.2 is particularly appropriate for providing policy makers with quantitative figures about the desirable and feasible reduction levels of carbon dioxide emissions.

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1. INTRODUCTION

The infinitely-lived agent (ILA) and overlapping generations (OLG) approaches towards climate change modeling have different views on intergenerational equity. In ILA models, the presence of an “immortal” representative agent, responsible for optimizing the (discounted) utility sum of both present and future generations, provides altruism between current consumers and their descendants, even if the latter are born in the far future. In OLG models, motives to leave bequests or behave altruistically are usually absent, especially regarding generations living in times distant from now. This chapter presents the OLG model ALICE 1.2. It is pointed out that the two approaches towards climate change modeling can in various circumstances, contrary to current claims in the literature, lead to rather different policy recommendations.

Until recently, climate change modelers have mainly used the ILA approach for assessing climate change policies that aim at reducing the anthropogenic emissions of carbon dioxide. Among various existing ILA models are notably those of Peck and Teisberg (1992), Nordhaus (1994) and Manne *et al.* (1995). In the ILA approach, also named after Ramsey, it is assumed that future generations can be represented by a single consumer living over an infinite period of time. This immortal agent acts as a representative on behalf of all future generations, by possessing the rights to decide on the amounts of investment and savings of the entire present and future population. The agent governs both physical and environmental capital endowments, of both present-day and future generations.

In many respects, the Ramsey approach is appropriate to study questions like the abatement of carbon dioxide emissions and the mitigation of an enhanced greenhouse gas effect. More generally, if used for the analysis of the allocation of assets and resources across generations, this approach achieves equity between generations by letting each generation’s utility depend only on its own consumption, and adding the resulting utility levels by means of a certain weight procedure using a properly chosen discount factor. As Solow (1986) indicated, the discounted sum of utility levels constitutes a proper measure of social performance. The Ramsey modeling framework allows for incorporating concerns of intergenerational equity.

On the other hand, good reasons exist for not adopting the ILA method, but for using an OLG framework instead. In an OLG model, consumers do – in principle – not behave altruistically, since agents are normally merely assumed to save during working years and consume all their savings from the moment they retire. The life-cycle of consumers and the demographic structure of a society thus play an important role in an OLG analysis, while the standard ILA approach neglects possible changes in the composition of a population. Given the demographic shifts that will occur during the 21st century (World Bank, 1994), this is the first fact in favor of an OLG analysis. Second, an OLG analysis reflects analytically in a realistic way the fact that human beings live through a finite time span, in a world which to good approximation can be considered as open-ended. Marini and Scaramozzino (1995) underline the need for the use of a framework reflecting a certain level of disconnection across generations, as ascertained in OLG models, since only then can the effects of different policy options on the trade-off between capital accumulation and environmental quality be determined appropriately. Third, an OLG model circumvents the rather abstract assumption that a representative agent exists who accomplishes establishing a social optimum for society as a whole, including both the present and distant future. Schelling (1995) points out, correctly, that it is hard to assume the existence of a leading agent who considers the well-being of future generations as beneficial to his own utility.

Of a different character is the argument, against the ILA and in favor of the OLG approach, regarding the way in which discounting is accounted for. As Howarth and Norgaard (1992) and Gerlagh and van der Zwaan (1999) point out, the ILA approach is unrealistic because the discount rate is imposed exogenously, whereas it ought realistically to be dependent on a range of variables and phenomena such as the intergenerational distribution of assets and resources, changes in demographic composition and the evolution of the population considered, as well as the possibility to implement policies designed to establish a sustainable economic development. The discount rate should therefore be integrated endogenously in economic models, even more so when one analyses climate change or the protection of the global environment, since the periods studied in these cases involve large time spans. The endogenization of the discount rate is accounted for in OLG models[1].

Stephan, Müller-Fürstenberger and Previdoli (1997) and Manne (1999) question whether one can conclude from the arguments made above that OLG models are superior to ILA models. They present a concise and computable general equilibrium model of climate change, which allows for a comparison of these two approaches. They conclude that OLG and ILA models do not differ significantly in their implication for policy making on greenhouse gas abatement. The authors suggest that both models lead to practically the same results with respect to future carbon prices, future shares of fossil fuels in energy consumption, and economic damages resulting from climate change. Stephan *et al*. (1997) find that only slight differences occur with respect to some macro-economic variables, when the modeler supposes that carbon emissions are taxed and the resulting revenues redistributed either entirely to the young or to the old generation. Stephan *et al*. (1997) and Manne (1999) conclude that the OLG approach does not differ fundamentally from the ILA method and is very similar in most respects. They state that OLG and ILA are thereby not competing, but rather complementary, approaches to the economic analysis of climate change. In our opinion, both modeling methods have merits and are indeed, as pointed out by these authors, useful complements for the analysis of global warming. Unlike these authors, however, we do not conclude that the results of the two approaches are rather similar.

Below, we demonstrate that, depending on the assumptions one makes on various economic conditions, such as *vis-à-vis* the specific nature of the public institutions designed for the protection of the environment, the OLG modeling results on climate change control can be subject to substantial variations. Thereby, climate change policy recommendations derived from OLG models can prove rather different from those resulting from the more traditional ILA models. Our numerical results confirm the formal analysis of Gerlagh and Keyzer (forthcoming). Furthermore, it is shown that in an OLG model many phenomena can be reflected in a more realistic way. The OLG approach is often more flexible, and allows readily for the simulation of, for instance, the

[1] It is possible to construct an OLG model in which altruism between generations drives the savings decisions, rather than concern for their own retirement. This leads to an OLG model that is much like an ILA model in its treatment of discounting (Barro, 1974).

ageing of the population, the grandfathering of a natural resource, or the implementation of a trust fund.

Section 2 of this chapter analyses the use of property rights for the protection of environmental resources against over-exploitation. It describes two possible public institutions: grandfathering and the set-up of a trust fund. Section 3 introduces the OLG method used for our analysis and describes the ALICE 1.2 model in a concise manner. Section 4 displays the various scenarios analyzed. Section 5 shows the main scenario results, and presents the time evolution of some important variables. Section 6 concludes.

2. PROPERTY RIGHTS AND THE PROTECTION OF ENVIRONMENTAL RESOURCES

For a long time, Pigouvian taxes have figured prominently in environmental economics to protect environmental resources, and to overcome inefficiencies created by strictly conservationist measures. Recently, the attribution of property rights over natural resources is receiving growing interest, presumably emanating both from the perception that markets can only function if private agents themselves have an incentive to prevent the use of natural resources without due payment, and from the understanding that the sums at stake might be substantial. Indeed, under appropriate pricing, the sustainable management of the natural environment could potentially become a profitable venture, given the vital role played by environmental services in the world economy. Costanza *et al*. (1997) estimate the present value of the (possibly indefinite) stream of environmental services at up to about 54 trillion US dollars in 1997 at world level. Although obviously such calculations are debatable, they give some hindsight into the relative importance of the natural environment.

In establishing new property rights over environmental resources, previously treated as public goods, there is a tendency to “grandfather” these resources, that is to endow the generation that is currently alive with their ownership. This implies that both man-made and natural capital is given in exclusive property to the present generation. The environmental resources become for the owners similar to man-made capital. The generation receiving the property rights sells the capital when it is old to the succeeding generation, in order to provide for its old age (pension). All following generations behave in a similar way.

However, grandfathering is not necessarily an ideal choice for environmental protection. From an ethical perspective, it can be argued that present generations ought not to be entitled to natural resources, since grandfathering capitalizes arbitrarily, such that present generations are allowed to deplete these resources before future generations can do so (Sen, 1982). Under grandfathering, future generations have to pay in order to prevent the present use of natural resources, so that *de facto* it implements the "victims pay" principle.

Not only from an *ex-ante* ethical perspective, but also from an *ex-post* equilibrium allocation perspective, grandfathering is not an evident option. Distributional issues matter and privatization of the environment does not safeguard its conservation. Pezzey (1992) shows with a simple ILA general equilibrium model that even if competitive markets are established for all natural resources, serious environmental degradation can persist. Mourmouras (1993) encounters the same problem with an OLG model, in which a full system of property rights is introduced through grandfathering. He shows that such a mechanism might be insufficient to prevent a gradual reduction of overall welfare.

As an alternative for grandfathering, we propose a more equitable, and possibly more sustainable, mechanism in which the ownership of resources is shared between current and future generations. Sharing property rights over natural resources between present and future generations requires an institution that acts as trustee for future generations, since only immediately succeeding generations are able to communicate directly.

Conceptually, the sequence of steps to establish such an institution could be as follows (see also Gerlagh and Keyzer, forthcoming). First, some public authority attributes the ownership of all previously free natural resources to a trust fund. Second, this authority rules that all consumers and firms should henceforth pay for the natural resources they use. Third, it allows the private sector to open trade with the trust fund, exchanging shares in the environment for shares in private-sector enterprises. Finally, the trust fund entitles every current and future consumer to an income claim, expressed as a share in the value of the trust fund's asset portfolio.

To determine the size of this income claim, the trust fund calculates the maximal level of production of environmental services that can be sustained forever, e.g. those provided by clean air and water, or stocks of fish, timber and the like. This output level is referred to as the basic consumption bundle. It might differ from the output level in a steady state of the environment, since substitution is allowed in the former. This maximally sustainable output defines the total claim to be shared among consumers. The trust fund's management maintains sufficient financial assets to meet this claim. The trust fund does not need to own environmental resources, but it is instructed to keep its asset value equal to the current value of the environmental stock that would be needed to generate the sustainable output. In an OLG model, it can be shown that if the instruction is followed during a given period, the trust fund will be able to pay the value of the basic consumption bundle to the consumers for that period and to follow the instruction for the next period, and so forth (Gerlagh, 1998, Section 4.3.3). If environmental degradation persists, future generations can no longer consume the quantity of environmental services on which the claim was based. In that case, their income from the trust fund will exceed actual expenditures on the environment. This revenue can be spent on other commodities.

The trust fund operates, as a compensation mechanism, on the "polluters pay" principle, since a generation that uses more of the resource than its entitlement will have to compensate future generations for the degraded environment in which the latter have to live. Early generations pay for the use of the environment insofar as this exceeds the regeneration capacity on which the claims are based. Through its stock holdings, the trust fund transfers the resulting revenues to the future generations who suffer environmental degradation. If future generations judge the preservation of natural resources essential, a trust fund provides for a mechanism which prevents environmental degradation, because it enables future generations to send the appropriate price signal to their predecessors.

3. MODEL SPECIFICATION

The model described in this section extends the usual integrated assessment modeling (IAM) of climate change in three respects: it contains a demographic transition, it specifies environmental damages as a loss of an environmental amenity associated to an environmental resource, and it specifies a transfer mechanism that distributes the value of this resource to consumers. This section focuses on a description of the demographic transition, and of consumer and producer behavior. The scenario description in the next section is complemented by a specification of the transfer mechanisms.

The model distinguishes discrete time steps, $t \in \mathbf{T} = \{1,\ldots,\infty\}$, each representing periods of 20 years. To solve the model numerically, it is truncated after a period T[2]. The first step corresponds to the interval 2000-2020, and in every interval a new generation is born. The model only describes the adult part of the life-cycle, i.e. from the age of 20 onwards. This implies that a two-period life represents an individual who reaches the age of 60, and a three-period life an individual reaching the age of 80. Consumption of children, in the age between 0 and 20, is accounted for by consumption of their parents. A generation is called young when its members have an age between 20 and 40; middle-aged are those individuals between 40 and 60, and old is the generation with members between 60 and 80.

Each generation is denoted by the date t on which it starts consumption; it then enters the model. The generation denoted t is born at time $t-1$[3]. Generations are of different size, denoted by n_i, with index i the first interval in which the generation consumes. The life-cycle lengths of generations are not identical. A demographic change is specified to represent increasing life expectancy, modeled as a transition from a lifecycle of two periods to one of three periods. This transition is assumed to take place entirely during the 21st century, that is during the first five intervals considered in the model. In the first interval, only a young and a middle-aged cohort coexist, without the presence of an old-aged generation. The middle-aged in the first interval die at the end of that interval. Twenty percent of the young die in the first interval, i.e. the middle-aged in the second interval live for a third period. Hence, in the third interval there is a small group of old consumers. Of the young generation in the

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[2] A full description of the technical elements behind this truncation procedure is beyond the scope of this chapter. ALICE 1.2 uses first order conditions, current prices, and a price deflator, and has beneficial solvability properties; numerical results are obtained in a relatively straightforward way. The model runs show that long time horizons, of e.g. 50 periods of 20 years each, can easily be dealt with. This is quite contrary to models that are solved by optimization, such as DICE (Nordhaus, 1994), which run into accuracy problems when the time horizon is extended too far. Whereas many optimization models can only be used up to about the year 2200, ALICE 1.2 allows simulations over several additional centuries at least. A model with an extended time horizon is a valuable instrument since environmental impacts of greenhouse gas emissions may last for centuries.

[3] Quantities referring to a particular generation are indexed by the subscript t. Alternatively, the label i is used where convenient.

second interval, i.e. the middle-aged of the third interval, forty percent live three periods, while the others live for only two periods. Life expectancy continues to increase linearly until all members of the generation that is young in the 2080-2100 interval live through a lifecycle of three periods. The life expectancy transition is then complete.

Now let n_t^i denote the size of generation *i* in interval *t*, so that n_i^i denotes the size of generation *i* when it starts consumption. We assume that no member of a generation dies before the start of the second consumption period of its life: $n_{t+1}^t = n_t^t = n^t$, for all generations *t*. As noted, the increase in life expectancy implies that the number of people living the full three periods increases linearly: $n_3^1 = 0.2 n_2^1$, $n_4^2 = 0.4 n_3^2$, and so forth, until $n_7^5 = n_6^5$. The time evolution of the size of a generation is defined recursively according to a logistic growth curve:

$$n^{t+1} = (a^n - (a^n - 1)(n^t / \overline{\mathrm{n}}))n^t , \tag{1}$$

where $\overline{\mathrm{n}}$ is the maximal size of a cohort, and a^n the growth factor if n^t is small with respect to $\overline{\mathrm{n}}$. In interval *t*, the population size N_t is given by:

$$N_t = n_t^{t+1} + n_t^t + n_t^{t-1} + n_t^{t-2} , \tag{2}$$

where n_t^{t+1} represents the children who enter the model, in terms of consumption, in period *t*+1. The other variables represent the young, the middle-aged and the old, respectively. The population at the beginning of a period can be thought of as the average of the population in the previous and the current period:

$$\widetilde{N}_t = \tfrac{1}{2}(N_{t-1} + N_t) . \tag{3}$$

The series $\widetilde{N}_t$ (for $t = 1,\ldots,\infty$) depends on the variables a^n, and $\overline{\mathrm{n}}$ via formulas (1) and (2). It also depends on the size of the generation, which starts consumption in 1960 and dies at the beginning of the first model-interval of 2000-2020. These parameters are calibrated such that the series approximates

World Bank (1994) data on global population. The results are shown in Table 1. The table also shows the modeled increase in life expectancy used in ALICE 1.2, which reasonably captures the main characteristics of the World Bank forecasts on life expectancy.

TABLE 1. *Population and Life Expectancy in ALICE 1.2*

	1960	1980	2000	2020	2040	2060	2080	2100	2200
Population, WB[1]	n.a.	n.a.	6.1.	7.7	9.0	9.9	10.6	11.0	n.a.
Population, ALICE 1.2[2]	n.a.	n.a.	6.1	7.7	9.0	10.0	10.7	11.1	11.1
Life expectancy at birth, WB[1]	n.a.	63.5	67.4	71.2	74.7	77.9	80.3	82.6	n.a.
Life expectancy at birth, ALICE 1.2	60.0	64.0	68.0	72.0	76.0	80.0	80.0	80.0	80.0

1. Population in billion people and life-expectancy in years, calculated from World Bank data (WB, 1994).
2. The population at the beginning of period *t* is taken to be the average population of periods *t*-1 and *t*. The population in period *t* includes the children that enter the model one period later.

Generations maximize their lifetime utility u(c^t,b^t), derived from rival consumption of the consumer goods during the life-cycle, $c^t = (c_t^t, c_{t+1}^t, c_{t+2}^t)$, and non-rival consumption of the resource amenity, for convenience referred to as "environmental services", $b^t = (b_t, b_{t+1}, b_{t+2})$. We omit the superscript *t* in the consumption of the resource amenity to stress that the amenity consumption is the same for all generations. By this definition of utility, an extension is made with respect to conventional IAMs, since the latter treat climate change damages as if they would constitute merely a decrease of man-made consumer goods. We find this assumption misleading, because global warming damages can be more realistically understood as a decrease in the quality and quantity of environmental functions, rather than as a reduction in the flow of man-made goods. Indeed, the IPCC (1996b, Section 1.3.2) recognizes that a decrease in biodiversity may be one of the major consequences of climate change. Our explicit specification of a resource amenity provides a means to incorporate this insight into a competitive equilibrium framework.

The consumption behavior of generations for which not all members live three periods is based on some further assumptions. For any member of a generation, until the beginning of the third period, only the probability of living three periods is known. At the beginning of the third period, a given member is either alive or not. Each member is supposed to maximize expected life-time utility subject to life span uncertainty. There are no non-intended bequests to future generations resulting from the uncertainty in lifetime (Hurd, 1989), because there is an intra-generational life-insurance company to which all members of a generation pay their savings in the second period of life. The insurance company repays the savings in the form of annuities to the living members of the generation in the third period, that is to those people who live into old age. Under this condition, the generation can be described by one representative consumer that maximizes aggregate utility, subject to one budget constraint, and as if there is perfect foresight[4]. The utility function u(.) employed is a nested CES function of the form:

$$\mathrm{u}(c^i, b^i) = [\sum_{t=i,\ldots,i+2} (\sigma)^{t-i} n_t^i ((c_t^i / n_t^i)^{1/(1+\nu)} (b_t)^{\nu/(1+\nu)})^{\frac{\rho-1}{\rho}}]^{\frac{\rho}{\rho-1}}, \tag{4}$$

where ρ=0.67 is the intertemporal elasticity of substitution, σ=1 is the consumers' time preference factor, and ν=0.1 is the constant share of the expenditures on the resource amenity relative to the man-made consumer good:

$$\varphi_t^i b_t = \nu c_t^i \;, \tag{5}$$

where φ^i_t are the so-called Lindahl prices for generation i in period t for non-rival consumption of the resource amenity, relative to the price of the man-made consumer good.

The first generation i=0 maximizes utility subject to its budget constraint:

$$max\ \{\ \mathrm{u}(c^0, b^0)\ |\ c_1^0 + \varphi_1^0 b_1 \ \leq w_1 l_1^0 + \psi_1 k_1 + H_1^0\ \}, \tag{6}$$

[4] The life-insurance concept is known from the Blanchard-Yaari-Weil model of 'perpetual youth' (see e.g. Blanchard, 1985). Marini and Scaramozzino (1995) use that model for the intergenerational analysis of environmental issues. In contrast to the perpetual youth model, we have discrete time periods and finite lifetime. Therefore, we give a more elaborate discussion of the uncertainty-certainty equivalence in the appendix.

while generations i=1,…,∞ solve:

$$max \{ u(c^i,b^i) \mid \sum_{t=i,\dots,i+2} \beta_i^t (c_t^i + \varphi_t^i b_t) \leq \sum_{t=i,\dots,i+2} \beta_i^t (w_t\, l_t^i + H_t^i) \}, \tag{7}$$

where prices are normalized so that the consumer good has price unity, β_i^t is the price deprecation factor from period i to period t (note that $\beta_i^i = 1$, and we also use the notation: $(1 + r_t) = (\beta_t)^{-1} - 1 = (\beta_t^{t+1})^{-1} - 1$, whenever convenient, where r_t is the interest rate at period t), w_t denotes the price of labor, l_i^t denotes the labor endowment, ψ_1 is the price of the man-made capital stock k_1 in the first period owned by the first generation, and H_t^i is the income which generation i receives in period t as its share in the value of the environmental resource. For generation i, utility maximization gives the following first order conditions:

$$\partial u(.) / \partial c^i = \lambda^i (1, \beta_i^{i+1}, \beta_i^{i+2}), \tag{8}$$

and

$$\partial u(.) / \partial b^i = \lambda^i (\varphi_i^i, \beta_i^{i+1}\varphi_i^{i+1}, \beta_i^{i+2}\varphi_i^{i+2}), \tag{9}$$

for a scalar Lagrange multiplier λ^i>0, such that the budget in (7) holds[5].

ALICE 1.2 includes a simple production sector for a man-made consumer good y_t, consisting of one private firm. It uses labor units l_t, emission units e_t, and a man-made capital stock k_t as production factors. The capital stock is itself produced by this production sector. We therefore assume that the capital stock is made up of the consumer good, and that it has to be replaced after use in one period. The production structure is based on a nested function, in which the intermediate good y_t^m is made of a Cobb-Douglas composite of capital and labor:

$$y_t^m = A_t k_t^{\alpha} l_t^{1-\alpha}, \tag{10}$$

[5] Note that $c^t = (c_t^t, c_{t+1}^t, c_{t+2}^t)$ and $b^t = (b_t, b_{t+1}, b_{t+2})$, so that both the left-hand-side and right-hand-side of these first order conditions represent 3-dimensional vectors.

where α=0.216 is the capital share, and A_t is a productivity coefficient[6]. The composite good y_t^m is used, together with emission units, in a quadratic production function:

$$y_t + k_{t+1} = y_t^m + \tfrac{1}{2}(\eta/\zeta_t)e_t\,(2\zeta_t - e_t/y_t^m), \tag{11}$$

where η is the maximal CO_2 tax at which net emissions become zero, and ζ_t is the maximum emission intensity when no carbon taxes are imposed. This becomes clear from the first order conditions for emissions:

$$p_t^e \geq \eta\,(1 - e_t/\zeta_t y_t^m)\ \perp\ e_t \geq 0, \tag{12}$$

where p_t^e is the price of emission units in period t and the complementarity sign '$\perp$' denotes that the left-hand inequality is binding (i.e. becomes an equality) if emissions are positive. The parameters η and ζ_t are chosen such that the optimal emission levels decrease by 1 percent for every 4 US$/tC price increase of emission units, and that the maximum emission levels follow the IS92a scenario (IPCC, 1992).

Because of constant returns to scale, the value of inputs equals the value of outputs:

$$y_t + k_{t+1} = w_t l_t + \psi_t^k k_t + p_t^e e_t, \tag{13}$$

where ψ_t^k is the price for capital in period t. Since capital is produced in the previous period, we have:

$$\psi_{t+1}^k = 1/\beta_t\,, \tag{14}$$

for t=1,…,∞. After substitution of the value equation (13), we have the following first-order conditions for labor and capital:

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[6] The value of α is calibrated such that the value of man-made capital constitutes 3 times the value of annual output. The value of 0.216 may seem rather low, but one has to keep in mind that it reflects the value share of current output that is attributed to investments made in the previous period. Because of the long time interval per period (20 years), a large part of capital is produced in the same period as in which it is used and is thus not accounted for in k_t. This effect decreases the value of α relative to models that have shorter time periods. The value of A_t is calibrated such that in the first period gross output is equal to 38.4 trillion US$/yr (1990 market prices), and increases by 3 percent per year. For a detailed calibration analysis, see Gerlagh (1998b, Section 6.2).

$$w_t l_t = (1-\alpha)(y_t + k_{t+1} - p_t^e e_t), \tag{15}$$

and

$$\psi_t^k k_t = \alpha(y_t + k_{t+1} - p_t^e e_t). \tag{16}$$

The fact that ALICE 1.2 extends existing IAMs by specifying an explicit resource amenity is in accordance with the environmental concerns underlying the issue of climate change. Peck and Teisberg (1992) and Nordhaus (1994) have much contributed to the development of stylized economic IAMs by providing highly simplified representations of biogeochemical interactions which are useable in macro-economic models. The typical simplified aggregate representation employed links emissions to concentrations, concentrations to temperatures, and temperatures to damages. However, regarding the calculation of impacts of climate change, the scientific understanding is grossly insufficient to warrant even something like a “best guess” (IPCC 1996a, Section 6.2.13). In general, it is assumed that damages caused by climate change will outweigh its benefits. The lack of knowledge is unmistakably revealed by sensitivity analyses carried out with a variety of different damage functions. These damage functions are supposed to provide a reduced form of many complex damages associated with climate change, such as the loss of coastal zones due to sea level rise, the loss of biodiversity, the spread of vector borne diseases, and the occurrence of extreme climate events. Some damage functions take the global temperature as arguments, others take the rate of increase of global temperature as an argument. Some damage functions are quadratic, others are of higher or lower order (cf. Tol 1995). The lack of understanding of damage functions is recognized by the IPCC (1996a, Section 6.2.13). In our model, we therefore restrict the resource specification to a simple linear relationship between emissions and resource amenities, and choose parameters resembling the damage estimates listed by the IPCC (1996a, Table 6.4).

Let s_t be the resource stock from which e_t units are subtracted each period:

$$s_{t+1} = s_t - e_t\,. \tag{17}$$

The exhaustible resource has amenity value b_t. We follow Krautkraemer (1985) and assume that the amenity value is proportional to the stock level:

$$b_t = s_t / s_1 \ . \qquad (18)$$

Thus, b_t is measured as an index, with maximum output b_t=1. The environmental firm maximizes the value of its output, $\sum_{t=1,\dots,\infty} \beta_1^t (p_t^e e_t + p_t^b b_t)$, subject to (17) and (18), and given the initial resource stock k_1. Let p_t^b be the price of the environmental amenity b_t, and ψ_t^s the price of the resource stock at the beginning of period t, so that $\beta_t \psi_{t+1}^s$ is the dual variable associated to (17) under profit maximizing, and p_t^b is the dual variable of (18). The first-order conditions read:

$$p_t^e \leq \beta_t \psi_{t+1}^s \qquad \perp \ 0 \leq e_t, \qquad (19)$$

$$\beta_t \psi_{t+1}^s + p_t^b / s_1 = \psi_t^s, \qquad (20)$$

where the ⊥-sign refers again to complementarity conditions: the constraint on the left is binding if the right-hand side is a strict inequality. Because of constant returns to scale in (17) and (18), for every period, the zero profit condition holds:

$$\psi_t^s s_t = p_t^e e_t + p_t^b b_t + \beta_t \psi_{t+1}^s s_{t+1} \ . \qquad (21)$$

This equation states that the value of the resource, $\psi_t^s s_t$, is equal to the value of its output. Written out for the entire time horizon, this becomes:

$$\psi_t^s s_t = \sum_{\tau=t,\dots,\infty} \beta_t^\tau (p_\tau^e e_\tau + p_\tau^b b_\tau) \ . \qquad (22)$$

It follows from the first-order conditions (12), (19), and (20) that if the future value of the resource amenity is sufficiently high relative to the maximal productivity of the extracted resource, $\eta < \beta_t \psi_{t+1}^s$, no extraction will take place. For zero extraction, the extraction price can take any value on the interval $[\eta, \beta_t \psi_{t+1}^s]$. However, the particular choice has no effects for the real variables. This completes the description of producer behavior.

To close the markets, we have the commodity balance for labor,

$$l_t = l_t^{t-2} + l_t^{t-1} + l_t^t, \tag{23}$$

as well as for the consumer good,

$$c_t^{t-2} + c_t^{t-1} + c_t^t = y_t. \tag{24}$$

Non-rivalry of the demand for the resource amenity implies that consumers should agree about the amenity level, so that Lindahl prices should add up to the production price:

$$p_t^b = \varphi_t^{t-2} + \varphi_t^{t-1} + \varphi_t^t. \tag{25}$$

The regulatory mechanism for controlling resource extraction and distributing income from the natural resource, as well as the corresponding regulations, are specified in Section 4. Here, it suffices to note that the Lindahl equilibrium represents an economy governed by a mixture of competitive markets and policies to achieve collective action. We impose the requirement that the income H_t^i, which is distributed among consumers, should balance with the value of the natural resource:

$$\psi_1^s s_1 = F_1, \tag{26}$$

where F_t measures the value of total assets to be reserved in period t for meeting future claims. This value can be defined as:

$$F_t = \sum_{\tau=t,\ldots,\infty} \beta_t^\tau H_\tau = \sum_{\tau=t,\ldots,\infty} \beta_t^\tau (H_\tau^{\tau-2} + H_\tau^{\tau-1} + H_\tau^\tau), \tag{27}$$

which recursively is written as:

$$F_t = H_t^{t-2} + H_t^{t-1} + H_t^t + \beta_t F_{t+1}. \tag{28}$$

The income claim is differentiated by date of accrual using the super- and subscripts as $H^t = H_t^t + H_{t+1}^t + H_{t+2}^t$; this allows us to define the period-specific claim as $H_t = H_t^{t-2} + H_t^{t-1} + H_t^t$. Note that generation t=0 only has a claim H_1^0 to the resource.

We are now in a position to specify the savings-capital balance, which has a central role in the scenario analysis. Let S_{t+1}^{t} and S_{t+2}^{t} represent the savings of generation t at the beginning of period t+1 and t+2, respectively. These are defined by the expenditure budgets when young,

$$\beta_t S_{t+1}^t = w_t l_t^t + H_t^t - c_t^t - \varphi_t^t b_t\,, \tag{29}$$

and when middle-aged,

$$\beta_{t+1} S_{t+2}^t = S_{t+1}^t + w_{t+1} l_{t+1}^t + H_{t+1}^t - c_{t+1}^t - \varphi_{t+1}^t b_{t+1}\,. \tag{30}$$

The life-cycle budget constraint in equation (7) ensures that savings are exhausted when old:

$$0 = S_{t+2}^t + w_{t+2} l_{t+2}^t + H_{t+2}^t - c_{t+2}^t - \varphi_{t+2}^t b_{t+2}\,. \tag{31}$$

The capital-savings balance equals total savings, which consists of private savings plus the assets held by the trust fund, with the value of capital, which consists of man-made capital and the resource value:

$$S_t^{t-1} + S_t^{t-2} + F_t = \psi_t^k k_t + \psi_t^s s_t\,. \tag{32}$$

Validity of the savings-capital equation for t=2 is ensured by summation of (6), (21), (25) multiplied by the amenity value b_1, and (29), and subtracting (13), (23) multiplied by wages w_1, (24), (26) and (28). After using (14) for substitution, we have:

$$\beta_1 (S_2^1 + F_2) = \beta_1 (\psi_2^k k_2 + \psi_2^s s_2)\,, \tag{33}$$

which is the second period savings-capital balance multiplied by the price factor β_1. For t=3,…,∞, validity follows from forward induction. This completes the model description. We can now define the equilibrium:

DEFINITION 1. A competitive equilibrium of model (6)-(32) is an intertemporal allocation supported by prices $w_t, p_t^e, p_t^b, \varphi_t^{t-2}, \varphi_t^{t-1}, \varphi_t^t, \psi_t^s, \psi_t^k, \beta_t$, for t=1,…,∞, that satisfy the production identities (10), (11), (17), (18), the first order conditions (8), (9), (12), (14), (15), (16), (19), (20), the commodity balances (23), (24), (25), the savings identities (29), (30), and the savings-capital balance (32), for a given regulatory policy that satisfies (26) and (27).

4. THE SCENARIOS

We define five scenarios. Production and consumption parameters are calibrated such that a reference ‘Business as Usual’ scenario (BAU) resembles the IPCC (1995) IS92A scenario. The second scenario (SUST) resembles a strict conservationist policy of minimizing resource extraction, or imposing even zero extraction, even if such is inefficient for given resource prices in equilibrium. The third scenario (GRANDF) restores efficiency by grandfathering the environmental resource to the first generation that is alive at the moment of the institutional set-up. In the fourth scenario (FUND), a trust fund is established to share property rights over the environmental resource with future generations. All these scenarios are based on the OLG concept in which savings balance with the capital stock; see equation (32). The fifth scenario (ILA) abstracts from the savings-capital budget. It instead invokes the Ramsey rule that links the interest rate with consumption growth.

We abstain here from an extensive description of the BAU scenario, since it is rather conventional. The three alternative regulatory mechanisms of ‘zero extraction’, ‘grandfathering’ and ‘trust fund’ involve specific rules for controlling natural resource extraction, and distributing the resource value, while meeting the intertemporal budget constraint (26).

SUST scenario

The second scenario (SUST) directly regulates the resource use by abandoning all resource extraction. This amounts to including the restriction:

$$e_t = 0. \tag{34}$$

The level of the resource amenity is now maximal: b_t=1. This scenario exempts all generations from paying for the non-rival consumption of the resource amenity. This can be represented through an income claim that is equal to the value of non-rival consumption,

$$H_t^t = \varphi_t^t \tag{35}$$

and

$$H_{t+1}^t = \varphi_{t+1}^t, \tag{36}$$

so that the budget equation becomes:

$$c_t^t + \beta_t^{t+1} c_{t+1}^t + \beta_t^{t+2} c_{t+2}^t = w_t\, l_t^t + \beta_t^{t+1} w_{t+1} l_{t+1}^t + \beta_t^{t+2} w_{t+2} l_{t+2}^t. \tag{37}$$

The zero extraction policy treats the natural resource as an exogenous factor, and reduces the economy to a one-consumer-good one-capital-stock production economy. However, in this economy, it is possible that the interest rate becomes negative, leading to a dynamically inefficient equilibrium. Indeed, a numerical analysis reveals that in our economy, the demographic transition induces an increase in savings to account for the longer retirement period. This, in turn, decreases the interest rate to a negative value. In theory, it is possible to restore dynamic efficiency by introducing negative fiat money into the economy (Gale, 1973). However, the required amount of fiat money cannot be calculated in advance without solving the equilibrium, and thus, cannot be treated as a fixed endowment. Alternatively, we introduce a 'non-negligible claim' that is given to the first generation, and which in the long term acts as negative fiat money (see Gerlagh, 1998, Sections 3.2.5 and 3.3.1 for a full discussion). We assume that there is a public authority, which can levy taxes, both now and in the future. This authority issues a freely tradable claim and pays the owner a real interest. In ALICE 1.2, a fixed share $0<\gamma<<1$ of the value of labor endowments. The payments by the public authority are balanced with taxes levied during the same period, so that the claim induces an income transfer from all owners of labor endowments to the owner of the claim. Let the value of the claim be denoted by χ_t, given by:

$$\chi_t = \gamma \sum_{\tau=t}^{\infty} \beta_t^{\tau} w_t\, (l_t^t + l_t^{t-1} + l_t^{t-2}). \tag{38}$$

The first generation receives the claim for free, so that its budget (6) becomes:

$$c_1^0 + \varphi_1^0 b_1 \leq w_1 l_1^0 + \psi_1 k_1 + \chi_1 . \tag{39}$$

Future generations pay a tax that enables the public agent to meet his obligations. Their budget (7) becomes:

$$\sum_{t=i,\ldots,i+2} \beta_i^t (c_t^i + \varphi_t^i b_t) \leq \sum_{t=i,\ldots,i+2} \beta_i^t (1-\gamma) w_t l_t^i . \tag{40}$$

The claim ensures that the first generation owns a non-negligible part of the total endowments value, and thus, dynamic efficiency is restored.

GRANDF scenario

The third scenario (GRANDF) extends private ownership to environmental resources. It grandfathers the entire natural resource to the first generation[7]. Future generations will have to pay to prevent pollution. This can be interpreted as applying a "victims pay" principle. Formally, the scenario is defined by the income distribution rule

$$H^0 = \psi_1^s s_1 , \tag{41}$$

and

$$H^t = 0 , \tag{42}$$

for t=1,…, ∞. There is no further intergenerational transfer: F_t=0. The natural resource becomes a 'normal' capital good, whose value is equal to life-cycle savings:

$$S_t^{t-1} + S_t^{t-2} = \psi_t^k k_t + \psi_t^s s_t . \tag{43}$$

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[7] In actual practice, emission permits are often grandfathered to the firms that are currently polluting. Since these firms are owned by the current old generation, this amounts in our model to awarding the property rights over the environment to the first generation.

Unlike the 'zero extraction' policy, the extracted resource can now be bought by firms. All generations have to pay for their non-rival use of the resource amenity. The budget constraint for all generations t=1,…,∞ becomes:

$$\sum_{t=i,\ldots,i+2} \beta_i^t (c_t^i + \varphi_t^i b_t) \leq \sum_{t=i,\ldots,i+2} \beta_i^t w_t l_t^i \,. \tag{44}$$

FUND scenario

The fourth scenario (FUND) involves a trust fund, which entitles every generation to the same income claim as in the zero extraction policy case, i.e. to one unit of the resource amenity:

$$H_t^{t-1} = \varphi_t^{t-1} \tag{45}$$

and

$$H_t^t = \varphi_t^t \,, \tag{46}$$

for t=1,…, ∞. The trust fund is endowed with the initial value of the biogeochemical system

$$F_1 = \psi_1^s s_1 \,, \tag{47}$$

which is exactly sufficient to meet the commitments expressed in equation (26). In every period, the transfers paid are subtracted:

$$F_{t+1} = F_t - H_t \,. \tag{48}$$

Consequently, the trust fund holds sufficient assets to meet future obligations, in accordance with equation (27). However, in contrast to the zero-extraction policy case, the income claims are not identical to the output of the biogeochemical system. We must show that these income claims sum to the initial value of the biogeochemical system. Multiplying (20) by s_1 gives:

$$\psi_t^s s_1 = p_t^b + \psi_{t+1}^s s_1 \,. \tag{49}$$

Therefore, the trust fund can meet its commitments in every period if it holds assets of value $F_t = \psi_t^s s_1$, starting from $F_1 = \psi_1^s s_1$. This ensures that the distribution rule satisfies equation (26) and that although all generations have to pay for their non-rival use of the resource amenity, their real income claim exceeds the actual value of the resource amenity. The budget constraint now reads:

$$\sum_{t=i,\dots,i+2} \beta_i^t (c_t^i) \le \sum_{t=i,\dots,i+2} \beta_i^t (w_t l_t^i + \varphi_t^i (1 - b_t)). \tag{50}$$

The last two terms on the right-hand side are compensations for reductions in environmental quality, relative to the undepleted level (which has b=1).

The three regulatory scenarios (SUST, GRANDF, and FUND) can be characterized by two parameters, η and γ, which describe the claims of future generations for a given natural resource level, and the use of a non-negligible claim to ensure dynamic efficiency. Thus, we can rewrite the budgets (29) and (30) as:

$$\beta_t S_{t+1}^t = (1-\gamma) w_t l_t^t - (1 - (\eta / b_t)(\nu/(1-\nu))) c_t^t, \tag{51}$$

and

$$\beta_{t+1} S_{t+2}^t = S_{t+1}^t + (1-\gamma) w_t l_t^t - (1 - (\eta / b_t)(\nu/(1-\nu))) c_t^t, \tag{52}$$

where we can represent the first generation via:

$$S_1^0 = \psi_1^k k_1 + (1-\eta)\psi_1^s s_1 + \chi_1, \tag{53}$$

and the capital-savings balance (32)

$$S_t^{t-1} + S_t^{t-2} = \psi_t^k k_t + \psi_t^s (s_t - \eta s_1) + \chi_t. \tag{54}$$

ILA scenario

The fifth scenario (ILA) has a different character. It is based on a dynastic perspective rather than on an OLG approach. The ILA scenario is not subject to the capital-savings budget constraint expressed by equation (54). Instead, it assumes the Ramsey rule, which directly links the interest rate to per capita consumption growth:

$$\beta_t = \sigma^p (c_t / N_t)/(c_{t+1} / N_{t+1}), \qquad (55)$$

where $0<\sigma^p<1$ is the fictitious planner's time preference factor, set to 0.44 for the analysis in this paper, representing a pure rate of time preference of 4 percent per year[8].

5. SCENARIO RESULTS

The BAU and SUST scenarios are inefficient since they do not set a price for current resource use based on future benefits of resource conservation. The three efficient scenarios (GRANDF, FUND, ILA) differ amongst each other with respect to the distribution of welfare. This difference can be characterized through the evolution of the interest rate over time, as shown in *FIGURE 1*. The ILA scenario shows a pattern that is most comparable with the existing IAMs, most of which are based on the ILA approach. The interest rate slowly decreases because of the assumed decrease in economic growth, see (55). The OLG scenarios show a much sharper fall in the interest rate, indicating a significant difference between ILA and OLG modeling. In the OLG approach, the savings rate increases during the 21st century because of the increased need for pensions in an ageing society. In the long run, the increased savings press the interest rate downwards, a phenomenon not captured in the ILA approach.

[8] The planner's rate of pure time preference is at the high end of the values found in the literature. This choice maintains consistency with OLG models where interest rates can reach relatively high levels in early periods as compared to most IAMs.

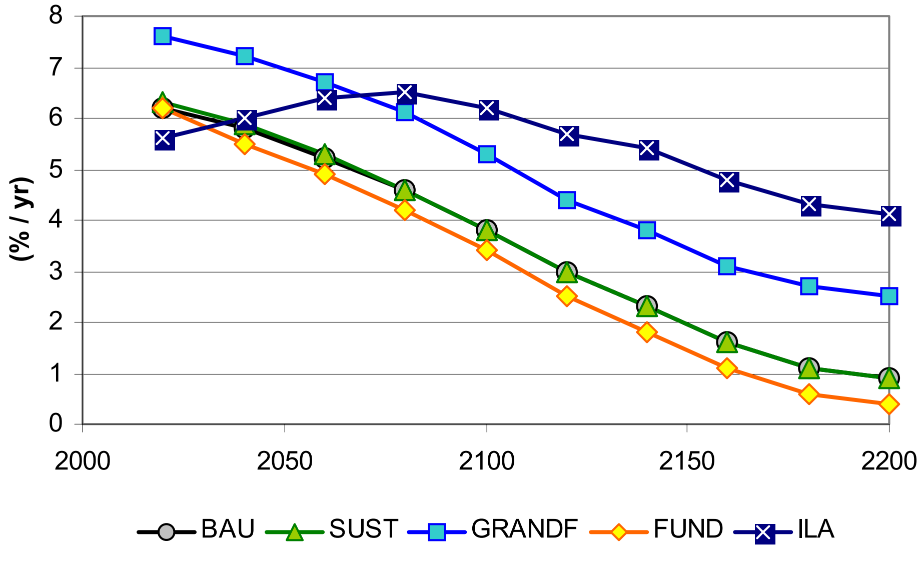

FIGURE 1. *Interest rates*

Within the series of OLG scenarios, we find a difference between the GRANDF scenario, with relatively high interest rates, and the FUND scenario, with relatively low interest rates. This can be understood as follows. Under the GRANDF scenario, the resource is capitalized and becomes private property. The total value of the capital stock increases, requiring increased savings to restore the balance. This causes an increase in the interest rate of about 1 percent per year as compared to the BAU scenario. The distance between the two scenarios pertains throughout the dynamic path. If the environmental resource is treated as public property (scenario SUST), the public savings increase by the same amount as the increase of the capital stock, so that the interest rate remains invariant with respect to the BAU scenario (to which the model is calibrated)[9]. If a trust fund is established (scenario FUND), the environmental resource is also treated as public property. The FUND scenario, however, has an important difference with the SUST scenario. A short-fall of the resource level with respect to its initial level leads to extra public savings[10].

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[9] In relation (54) we have $\eta=1$ and $s_t=s_1$. For an elaboration of this reasoning, including an explanatory picture, see Gerlagh and van der Zwaan (1999).

[10] In relation (54) we now have $\eta=1$ and $s_t<s_1$.

In the long run, the additional public savings further decrease the interest rate from 1 percent per year to 0.5 percent per year. The distribution of property rights over the environmental resource turns out to have major implications on the interest rate. As shown below, this affects the resource use as well.

The assumed carbon dioxide emissions decrease by one percent for each 4 US$/tC increase in the tax imposed is an average of values appearing in the literature, ranging from 1 to 6 US$/tC (see Cline, 1992). This value implies that a 100 % CO_2 emission abatement corresponds to a tax level of 400 US$/tC. The SUST scenario assumes a tax of 400 US$/tC from the year 2000 onwards, as can be seen in *FIGURE 2*. The only mechanism in our model responsible for reductions in carbon dioxide emissions is the imposition of carbon taxes. We abstract from endogenous technological learning, as well as from transition costs associated with a shift towards a carbon-free energy technology.

In the GRANDF scenario, the carbon emission price slowly increases from nearly zero in 2000 to 50 US$/tC in 2050, after which it starts increasing more rapidly to reach values close to 400 US$/tC shortly after 2100. The CO_2 emissions (see *FIGURE 3*) in this scenario increase slowly up to about the year 2050, after which they start falling rapidly down to levels close to zero shortly after 2100. In the FUND scenario, the carbon emission price increases rapidly from the very start of the simulation in 2000, where it has already a value close to 50 US$/tC. By 2050 it reaches values nearing 400 US$/tC. The CO_2 emissions (see *FIGURE 3*) in this scenario are rather stable in the first modeling period, but decrease rapidly down to levels close to zero around the year 2050. From a comparison between GRANDF and FUND, one concludes that altering the analysis from a “victims pay” to a “polluters pay” perspective, by the introduction of a trust fund, substantially shifts upwards the carbon dioxide emission tax curve. As usual in a general equilibrium model, and contrary to the notion commonly referred to as the Coase Theorem (Coase, 1960), the intergenerational redistribution of property rights through the trust fund affects the allocation of resources and hence the level of resource extraction. A formal proof for a simpler economy is given in (Gerlagh and Keyzer, forthcoming).

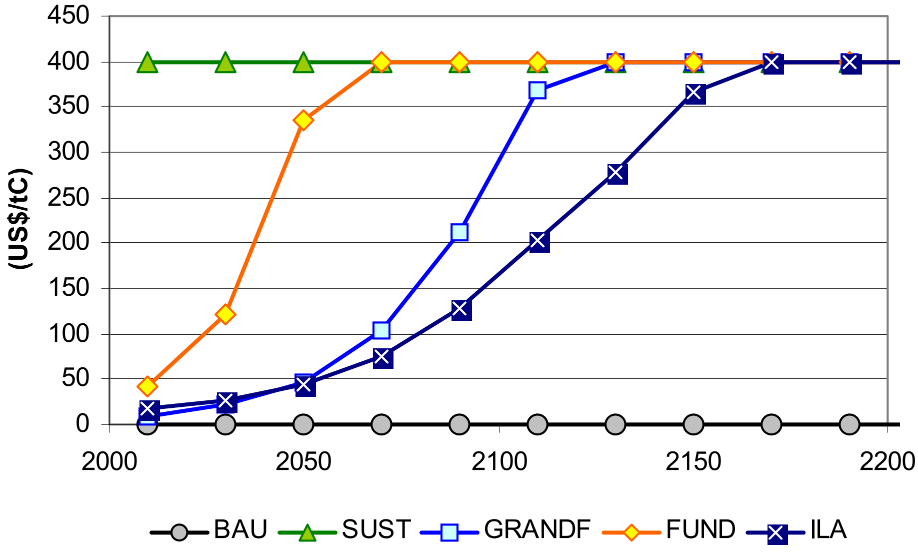

FIGURE 2. *Carbon taxes*

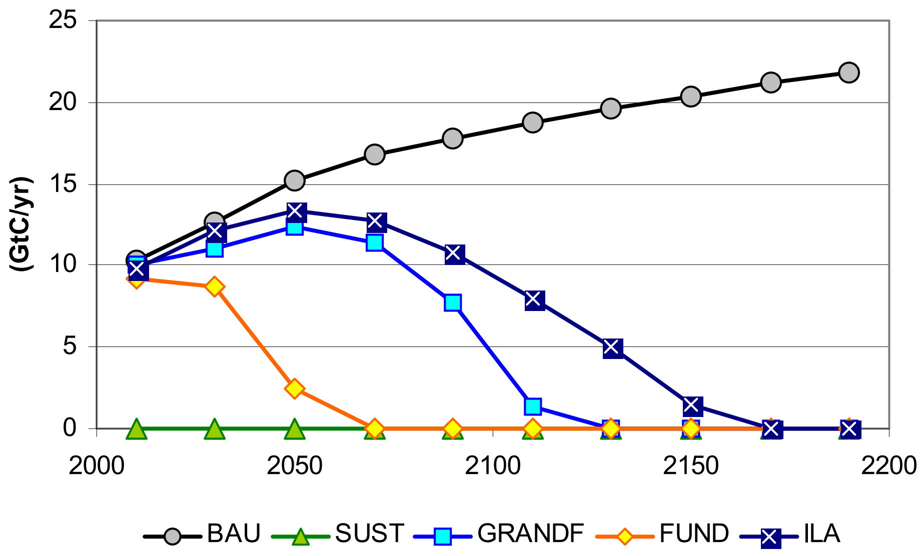

FIGURE 3. *Carbon dioxide emissions*

Apart from rigid conservation measures such as those under the SUST scenario, using a trust fund (FUND) achieves most radical CO_2 emission reductions. Grandfathering (GRANDF) is less favorable for climate change reduction, but still leads to more stringent emission reductions than are found under the assumption of a fictitious infinitely-lived agent that takes care of the welfare distribution over all generations. Of course, the ILA approach is a significant improvement as compared to Business as Usual (BAU). From this comparison, one sees that at the numerical level, OLG models provide substantial different results from ILA models. As for the theoretical analysis, additional insights in mechanisms and policy instruments to reduce anthropogenic climate change can be gained.

Finally, we compare the results of the five scenarios for the consumption of the man-made good and the induced temperature change. In *FIGURE 4*, consumption of the man-made good is shown relative to the BAU scenario. The stringent zero emission measures under a strong sustainability policy (SUST) cut the consumption levels by nearly 6 percent during the first decades. Over time, as dependence of the economy on fossil fuels decreases, the reduction of consumption decreases as well. The trust fund (FUND) scenario has less stringent emission reductions, particularly during the first periods, which is reflected in the consumption path that stays closer to the BAU path. Grandfathering (GRANDF) capitalizes the value of the environmental resource and gives it to the first generation, which uses it to increase its consumption at the costs of investments in man-made capital. As a result, consumption in the first period is rather high initially, but soon decreases after that. The dynastic (ILA) scenario is not directly comparable with the other scenarios, since in this case the intergenerational and intertemporal distribution of consumption is subject to the Ramsey rule, which does not directly relate to OLG equilibria.

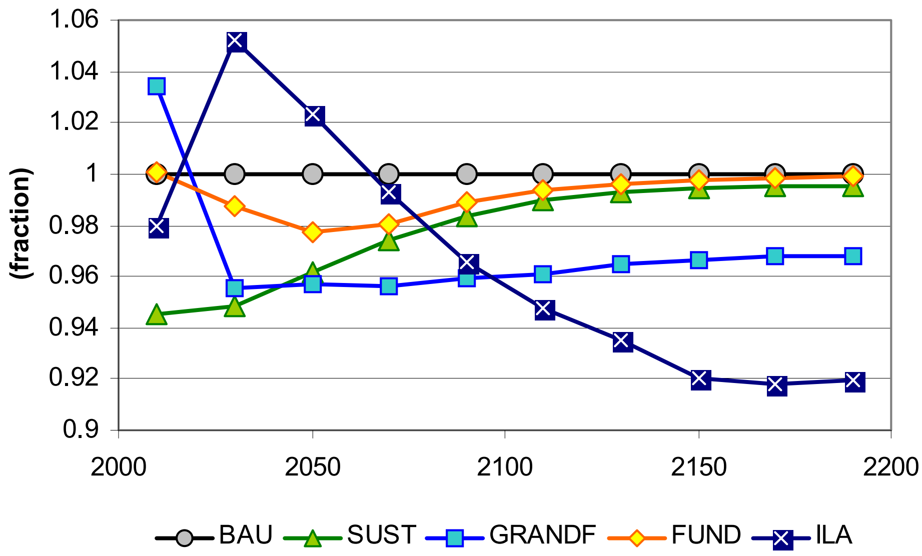

FIGURE 4. *Consumption of the man-made good, relative to BAU*

FIGURE 5 shows the calculated temperature increase, relative to pre-industrial levels, consistent with the emission paths of *FIGURE 3*. We used the one-box carbon model as employed in DICE (Nordhaus, 1994), linking CO_2 emissions to concentrations and to temperatures, based on a climate sensitivity parameter of 3 degrees Celsius for a doubling of the atmospheric CO_2 concentration. Under business as usual (BAU), temperature increases approximately linearly by nearly 0.2 degrees Celsius per decade. Furthermore, *FIGURE 5* shows that changes in the paths for temperature change lag behind the emission reductions shown in *FIGURE 3* for at least fifty years. Policy making has to be performed on a very long time horizon in order to realize an effective climate change control. Even under zero emissions (SUST), temperature continues to increase for the next 50 years, before temperature slowly returns to its pre-industrial level. The immediate and radical emission reductions under the trust fund (FUND) as compared to business as usual only lead to a deviation of the temperature path after 2050. Grandfathering the resource (GRANDF) or using a dynastic model (ILA) for calculating optimal emission reduction paths brings about no significant decrease in the temperature change in the next century, as compared to business as usual.

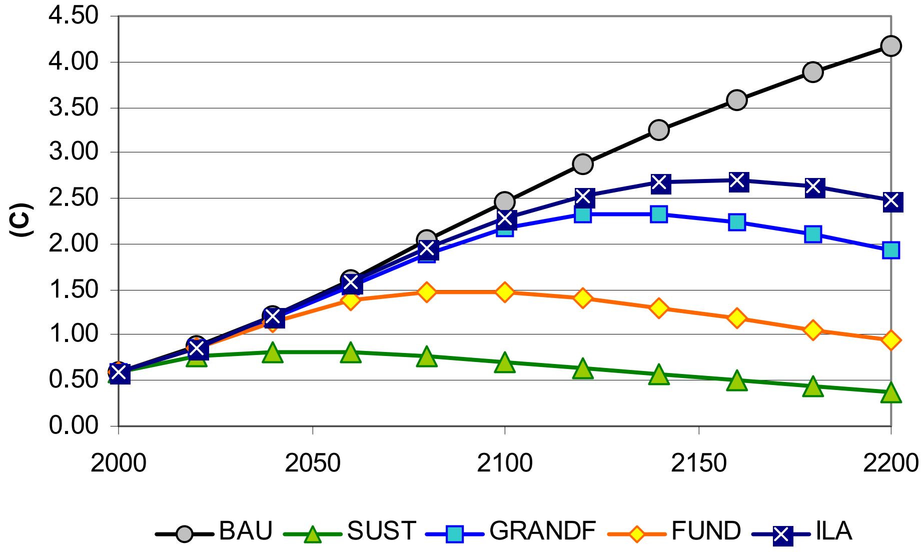

FIGURE 5. *Calculated temperature change*

6. CONCLUSION

In this chapter, we come to the following conclusions. In our opinion, the use of OLG models for the analysis of climate change control differs more fundamentally from that of ILA models than has been suggested in the literature. In particular, the results we obtain with the OLG model ALICE 1.2 are notably different from those of the OLG model by Stephan *et al.* (1997) and Manne (1999). One of the reasons is that they do not take into account the consequences of possible changes in demographic composition and population size. In addition, Stephan *et al.* (1997) assume that generations live for two periods only.

The model ALICE 1.2 presented in this chapter treats demography in a quite different way. First, the fact that life is considered to consist of three periods renders the model more realistic. Second and more importantly, the population is allowed to age throughout the next century, a phenomenon that will undoubtedly reveal itself over the forthcoming decades.

Another reason for the difference between our results and those by Stephan *et al.* (1997) and Manne (1999) is that the models of the latter do not properly assume an intergenerational distribution of carbon tax revenues. Stephan *et al.* allow only a distribution of tax revenues to the young or the old, or a combination of these two, within the same period. Our model allows for a distribution of carbon tax revenues over all present and future generations, via the use of a trust fund.

Our model introduces two tools, grandfathering and the creation of a trust fund. The latter can truly allow for an equitable redistribution of natural resources, *in casu* a carbon-poor atmosphere, over an infinite sequence of generations.

ACKNOWLEDGEMENTS

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APPENDIX: UTILITY MAXIMIZATION UNDER UNCERTAIN LIFE-TIME

In this appendix, equivalence is shown between utility maximization under uncertain lifetime and utility maximization of a representative agent as described by (7). Under uncertain life-time, every individual consumer of generation i maximizes expected utility, E[u(.)],

$$E[\mathrm{u}(c^i, b^i)] = [\sum_{t=i,\ldots,i+2} (n_t^i / n_i)(\sigma)^{t-i} ((c_t^i / n_t^i)^{1/(1+\nu)} (b_t)^{\nu/(1+\nu)})^{\frac{\rho-1}{\rho}}]^{\frac{\rho}{\rho-1}}, \quad (56)$$

where n_t^i / n^i is the probability of being alive in period t, and c_t^i / n_t^i is per capita consumption of the rival man-made consumer good. For the young and middle-aged of generation t, the per capita budgets are given by:

$$c_t^t / n_t^t + \varphi_t^t b_t / n_t^t + \beta_t S_{t+1}^t / n_t^t = w_t l_t^t / n_t^t + H_t^t / n_t^t, \text{ and} \quad (57)$$

$$c_{t+1}^t / n_{t+1}^t + \varphi_{t+1}^t b_{t+1} / n_{t+1}^t + \beta_{t+1} S_{t+2}^t / n_{t+1}^t = S_{t+1}^t / n_{t+1}^t + w_{t+1} l_{t+1}^t / n_{t+1}^t + H_{t+1}^t / n_{t+1}^t . \quad (58)$$

If an individual is uncertain about his life-time, that is, uncertain as to whether he will live during the third period or not, insurance is bought from the savings of the second period of life, S_{t+2}^t / n_{t+1}^t, to buy an annuity for the third period. Those that live until the end of the third period receive the annuity as income, S_{t+2}^t / n_{t+2}^t. Note that, thereby, the insurance mechanism produces a transfer from those that live two periods to those that live three periods; the deposit paid by those who die is distributed over those that live,

$$S_{t+2}^t / n_{t+1}^t < S_{t+2}^t / n_{t+2}^t, \quad (59)$$

if $n_{t+2}^t < n_{t+1}^t$. The budget for the third period becomes:

$$c_{t+2}^t / n_{t+2}^t + \varphi_{t+2}^t b_{t+2} / n_{t+2}^t = S_{t+2}^t / n_{t+2}^t + w_{t+2} l_{t+2}^t / n_{t+2}^t + H_{t+2}^t / n_{t+2}^t . \quad (60)$$

Every individual maximizes utility (56) subject to the budget constraints (57), (58), and (60). It is now readily shown that the consumption-savings decision can be described by one representative consumer. Multiply the objective function (56) by n^i, sum the constraints (57), (58), and (60) after multiplication by n^t_{t2}, $\beta^t_{t+1} n^t_{t+1}$, and $\beta^t_{t+2} n^t_{t+2}$ respectively, and one arrives at the representative program (7).

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