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# Global Demographic Change, Carbon Emissions, the Optimal Carbon Price and Carbon Abatement

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## Abstract

This paper empirically analyses the prospective impact of global demographic change on the time path of the optimal carbon price, global emissions and global carbon abatement. The approach is to apply a simple Ramsey model in order to examine the effect of global demographic change on the fundamental drivers of the optimal carbon price and optimal abatement. The results suggest a policy trade-off to some extent between mitigating population ageing and mitigating climate change. The lower fertility scenario, which implies an older future population, results in lower carbon emissions and therefore a lower optimal carbon price. Policies to mitigate population ageing would therefore increase carbon emissions and increase the carbon price.

**KEYWORDS:** demographic change, carbon price, carbon emissions, abatement

# 1 Introduction and Policy Perspective

Population ageing and climate change are arguably the two dominant global socio-economic challenges of our time. This paper explores a particular relationship between these challenges.

Population ageing is no longer a phenomenon restricted to developed countries - it is gathering pace in developing countries. Although developing countries are still younger, the rate of demographic transition toward older societies is occurring much faster than it did for the more developed countries. For example, in the 30 years to 2005, which was a period of relatively large falls in fertility in more developed regions, the reduction in the total fertility rate in less developed regions was in fact twice the reduction that occurred for the more developed regions (United Nations, 2006). Over the next two decades, the population aged over 60 in less developed regions is expected to increase at 3 per cent per annum compared with 2 per cent for more developed regions. All ageing societies face major policy challenges, such as pension and health care reform, encouraging labour force participation of older workers, and managing lower growth in living standards.

The policy challenges of climate change mitigation and adaptation are equally, if not more, challenging. The United Nations Climate Change Conference in Bali in 2007 established, through the 'Bali Roadmap', official agreement among the 180 participating countries to develop an international policy framework with respect to climate change mitigation and adaptation. This process will continue at the Copenhagen Summit in December 2009 where the UN Secretary-General Ban Ki-moon has declared it his top priority to establish international agreement to a treaty to succeed the 1997 Kyoto Protocol which expires at the end of 2012. The consensus among participating nations is the need to seek agreement on targets for carbon dioxide ($CO_2$) emissions by 2020 and beyond. Cuts in $CO_2$ emissions require a non-zero price on carbon emissions which could have significant structural and distributional impacts within countries and internationally.

These two global policy challenges are linked through the impact that population ageing can have on carbon emissions, the optimal carbon price over time and therefore the optimal degree of carbon abatement over time. This in turn has implications for government policy regarding the carbon permit market. This paper explores these linkages. The results suggest that there may be a policy trade-off to some extent between mitigation of population ageing and mitigation of climate change.

The aim here is to examine the effects of global demographic change on the fundamental drivers of the optimal carbon price, emissions and abatement, using a simple Ramsey model[1]. This model takes the world economy as a single economy producing a single good that emits carbon as a pollutant. Hence this is not an exercise in modelling energy use and pollution by country, industrial sector, type of energy or type of pollution. Nevertheless, even is such a simple model the potential effects are shown to depend on a complex interaction of parameters and to be non-trivial in magnitude.

There has been very little consideration of the potential effects of prospective demographic change - in particular the effect of the population age structure - on the path of the optimal carbon price. A number of studies have established a link between household age composition and energy use with implications for carbon emissions (Lenzen et al., 2006; O'Neill and Chen, 2002; Wier et al, 2001; Yamasaki et al., 1997; Schipper, 1996). But these models are not optimal growth/saving models and therefore cannot consider potentially important feedback effects through, for example, changes in the marginal product of capital; and more importantly for the purposes here, these studies do not consider the socially optimal carbon price over time, nor optimal carbon abatement over time.

Dalton et al (2008) apply an optimal growth model with detailed modelling of energy inputs and households with age-specific consumption expenditures on goods with different energy intensities. The model is applied to United States data including detailed projections of household age structure. They project that population ageing in the U.S. could lower carbon emissions by up to 40 percent by 2100. Their emissions projections arise from private optimising decisions of households and firm. However, their model does not explicitly consider global demographic change, nor does it yield a path for the socially optimal carbon price or socially optimal carbon abatement. Other prominent applications of growth models in analysing climate change, with varying degrees of regional and sectoral disaggregation, include Stern (2006), Nordhaus (2000), McKibbin and Wilcoxen (1999); and for an earlier survey of a number of such models see Repetto and Austin (1997). These applications typically consider demographic change only through assumptions about aggregate population growth. There are no simulations of prospective changes in the global population age structure on the optimal carbon price and optimal abatement over time. As it will be shown in this paper, changes in the age structure can affect the optimal carbon price, even in a simple Ramsey model, via the marginal product of capital

[1] A Ramsey model (Ramsey, 1928) is a neoclassical growth model with endogenous saving. The other key features are: one good (both a consumption and capital good), perfect foresight of agents and exogenous technical progress.


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and the marginal damage function, which in turn depend on the interaction of a number of parameters.

The model applied in this paper is closer to those in Van der Ploeg and Withagen (1991), Ulph and Ulph (1994), Sinclair (1994) and Farzin (1996). Van der Ploeg and Withagen (1991) introduce the optimal control of pollution into a classic Ramsey model. They show how the socially optimal level of abatement and can be achieved using Pigouvian taxes. Unlike the model in this paper however, their model is not calibrated and does not consider the impact of demographic change. The other three studies just mentioned adopt a similar modelling approach and focus on the optimal path of a carbon tax. With the exception of Farzin (1996) their models are not calibrated and none of them consider the effect of demographic change. An important feature, however, of these Ramsey-like models for present purposes is the analysis of the forces and parameters that affect the optimal carbon price.

The remainder of the paper is organised as follows. Section 2 sets out the structure of the Ramsey model; more detail of the solution method and calibration is provided in the Appendix. Section 3 describes the global demographic projections that are sourced from the United Nations World Population Prosects and the associated Long Range Projections. This section also explains the mechanisms through which demographic change affects the optimal carbon price and optimal emissions abatement. Section 4 presents the results of the simulations including a sensitivity analysis; and Section 5 summarises the policy implications.

## 2 The Model

A social planner is assumed to maximise the following social welfare function:

$$V = \sum_{t=1}^{T} N_t U\left(\frac{C_t}{N_t}\right)\left(1+\theta\right)^{1-t} \qquad U' > 0; \;\; U'' < 0; \tag{1}$$

where $C_t$ is aggregate consumption, $N_t$ is population and $\theta$ is the rate of time preference.

The stock of the resource (such as coal) that generates carbon emissions when burnt is, for simplicity, assumed to be non-renewable but in sufficiently large supply to be effectively infinite. Hence there is no scarcity rent from the non-renewable resource. Ignoring the scarcity rent allows us to avoid the problem of the optimal path of resource extraction and focus on the optimal externality cost of emissions. For related models which relax this assumption see, for example, Ulph and Ulph (1994) and Farzin (1996).

The net flow of $CO_2$ emissions is a function of output of goods and services and the units of output allocated to emissions abatement:

$$D_t = \frac{\mu Y_t^{\omega}}{B_t^{\sigma}} \tag{2}$$

where $D_t$ is the flow of emissions during period $t$, $Y_t$ is output, $B_t$ is national expenditure on an emissions-abating technology, $\mu$ is a scaling parameter, and $\omega$ and $\sigma$ are, respectively, the output and abatement elasticity of emissions flow. The stock of emissions evolves according to

$$S_t = (1-\varepsilon) S_{t-1} + D_t \tag{3}$$

where $S_t$ is the stock of emissions and $\varepsilon$ is the natural rate of absorption of emissions from the atmosphere.

Output, $Y_t$, is a function of stocks of capital, $K_t$, emissions and labour, $L_t$:

$$Y_t = \frac{A_t K_t^{\gamma} L_t^{\gamma-1}}{\Omega S_t^{\eta}} \tag{4}$$

where $A_t$ is total factor productivity which grows at an exogenous rate, $a$. The capital stock evolves according to

$$K_t = (1-\delta) K_{t-1} + I_t \tag{5}$$

where $K_t$ is the stock of capital, $I_t$ is the flow investment and $\delta$ is the rate of depreciation of capital.

A closed economy is assumed, implying:

$$Y_t = C_t + I_t + B_t \tag{6}$$

The social planner maximises a Lagrangian subject to the above constraints:

$$\begin{aligned} L = &\sum_{t=1}^{T} N_t U\left(\frac{C_t}{N_t}\right)(1+\theta)^{1-t} \\ &-\sum_{t=1}^{T} \lambda_t \left(K_t - (1-\delta) K_{t-1} - Y_t + C_t + B_t\right) \\ &-\sum_{t=1}^{T} \phi_t \left(D_t - S_t + (1-\varepsilon) S_{t-1}\right) \end{aligned} \tag{7}$$

where $\lambda_t$ and $\phi_t$ are the shadow prices of capital and carbon emissions, respectively. The solution details including calibration of parameter values are given in the Appendix.


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The two equations of motion governing the path of the carbon price are

$$\phi_{t+1} = \frac{\phi_t + \left(\lambda_t - \phi_t D_{Y,t}\right) Y_{S,t}}{1-\varepsilon} \tag{8}$$

$$\lambda_{t+1} = \frac{\lambda_t - \left(\lambda_t - \phi_t D_{Y,t}\right) Y_{K,t}}{1-\delta} \tag{9}$$

where $D_{Y,t}$ is the marginal emissions from output, $Y_{S,t}$ (<0) is the marginal damage from emissions, and $Y_{K,t}$ is the marginal product of capital.

Some intuition may be helpful. The term $-\left(\lambda_t - \phi_t D_{Y,t}\right)$[2] is the net shadow price of a unit of capital, where $\phi_t D_{Y,t}$ is the marginal externality cost from a unit of capital and is subtracted because the future output that could be generated from a unit of capital causes emissions which have an externality cost of $\phi_t D_{Y,t}$. The shadow price of capital declines (in absolute value) over time because a unit of capital can generate output in all future periods and therefore a new unit of capital is more valuable if created today than in the future. This standard result is pointed out because it has an analogy with the shadow price of emissions as discussed below.

Equation (8) gives the time path of the shadow price of carbon emissions, $\phi_t$, and hence the socially optimal carbon price. Two factors put upward pressure, and one factor puts downward pressure, on the carbon price over time. Downward pressure comes from the marginal damage function, $Y_S$, which is negative and therefore decreases the carbon price over time. The reason is analogous to that for the decline in the shadow price of capital over time – that is, a unit of carbon emitted today does more aggregate harm over all time periods than a unit of carbon emitted in the future. Hence the shadow price, or externality cost, of a unit of carbon emitted today is higher than that of a unit emitted tomorrow. Note that the externality cost is reduced by the term $\phi_t D_{Y,t}$ because the damage to output in turn lowers future emissions.

Upward pressure on the path of the carbon price derives from two factors: the natural rate of absorption ($\varepsilon$) and the rate of return on capital, $Y_{K,t}$, because both factors reduce the future output costs of current emissions. The rate of absorption does so directly by reducing the physical stock of emissions. The return on capital

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[2] The inequality $\lambda_t < \phi_t D_{Y,t}$ holds for any plausible parameterisation, otherwise it would imply that the emissions damages from future output are so costly that it is not worth saving to increase future output.

is the discount rate to apply to future damages. Hence a higher return on capital lowers the present value of future damages which reduces the value of current emissions relative to future emissions and therefore dampens the downward path of emissions caused by $Y_{S,t}$. The result is that the higher the value of $Y_{K,t}$ the more likely is the carbon price to increase over time.[3] The rate of return on capital is in turn driven by two parameters: the pure rate of time preference ($\theta$) and the rate of technical progress, $a$. In a closed economy the rate of time preference affects the return on capital through the path of consumption which drives the path of the capital stock and therefore the marginal product of capital.

# 3 Demographic Projections and the Carbon Price

The demographic data are obtained from the United Nations, World Population Prospects, 2006 Revision which provides population for the world by age and sex in five yearly intervals up to 2050; and from the United Nations Long Range Projections, 2003 Revision, which provide projections of population, dependency ratios and other variables out to the year 2300. There are three variants: Low, Medium and High, which differ in their fertility assumptions. Under the Medium variant, total fertility in all countries is assumed to converge eventually toward a level of 1.85 children per woman. Under the High variant, fertility is projected to remain 0.5 children above the fertility in the medium variant over most of the projection period. Under the Low variant, fertility is projected to remain at 0.5 children below the fertility in the medium variant over most of the projection period.

Figure 1 plots the support ratio for each of the demographic scenarios, where the support ratio is given by $\left(\frac{L}{N}\right)_t = \frac{1}{1+d_t}$ and where $L$ is employment, $N$ is population, and $d$ is the dependency ratio defined as dependents per worker. Relative to the Medium scenario, the Low scenario generates a higher support ratio for the first 50 years followed by a permanently lower support ratio. This reflects the effect of lower fertility reducing the proportion of young dependents for an initial period which raises the support ratio, followed by a reduction in the working age share of the population and an increase in the proportion of older dependents which reduces the support ratio. The High scenario generates the

[3] This is one potential cause of a so-called "carbon price ramp" where the optimal carbon price starts out low and increases over time. In other models it can be due to the fact that at the present time creating physical capital is more productive than using resources to reduce emissions, but over time the rising cost of emissions shifts this balance towards emissions reductions, implying a rising carbon price (Nordhaus, 2007a).


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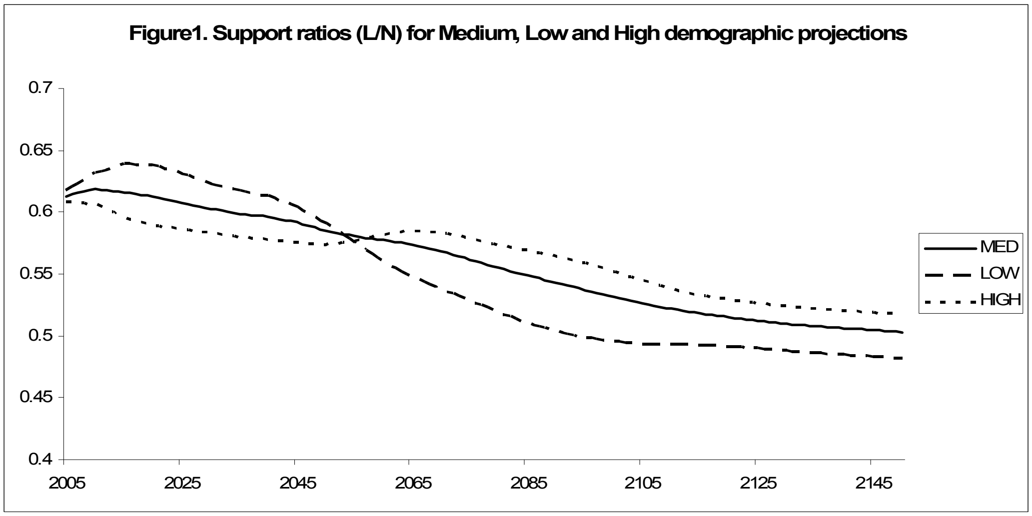
opposite pattern to the Medium scenario – a lower support ratio initially and a higher support ratio subsequently. The simulations determine the effect of these demographic projections on the path of the optimal carbon price and path of optimal carbon abatement.




## The effect of demographic change on the optimal carbon price and optimal carbon abatement.

Demographic change affects the carbon price through the marginal damage function, $Y_S$, and the rate of return on capital, $Y_K$.

The marginal damage function is given by

$$Y_{S,t} = -\eta \frac{Y_t}{S_t} \tag{10}$$

which indicates that marginal damages depend on the emissions intensity of output ($Y/S$) and the elasticity of output with respect to emissions, $\eta$. The higher is $Y/S$ the greater is the damage caused by a given increase in emissions. The Low scenario, for example, implies relatively lower employment growth and lower output, implying a lower $Y/S$ ratio. From (10) the effect is smaller marginal damages from emissions and therefore a smaller change in the carbon price over time (slower decline or a faster increase), with the result that the carbon price is higher under the Low scenario. This is borne out in the simulations discussed below.

Optimal carbon abatement at any time $t$ is determined by the first order condition (see Appendix) that the marginal cost of abatement equals the marginal benefit:

$$\lambda_t = \frac{-\phi_t S_{B,t}}{\left(1 - Y_{S,t} S_{B,t}\right)} \tag{11}$$

where $\lambda_t$ is the marginal cost of abatement, since output allocated to abatement could have been allocated to investment in physical capital or consumption. This is driven by the rate of return on capital, $Y_K$. The right hand side of (11) is the marginal benefit where the numerator is the social cost per unit of emissions multiplied by the marginal quantity of emissions abated, and the denominator is a deflator (>1) representing the marginal effect of abatement in lowering future output and emissions. Optimal abatement, $B_t$, is found by solving (11) for $S_{B,t}$ and using

$$S_{B,t} = -\frac{\sigma \mu Y_t^{\omega}}{B_t^{\sigma+1}} \tag{12}$$

to solve for $B_t$.

Lower fertility, reflected in the Low demographic scenario, affects the marginal return on capital, $Y_K$, through its effect on employment and on capital creation via saving. Initially the return on capital is lower due to a higher capital-labour ratio, but in the long term lower saving lowers capital creation which raises the return on capital. This long run effect implies a higher marginal cost of abatement because abatement uses resources that could have been allocated to physical capital. The lower output caused by lower employment also lowers the marginal benefit of abatement. Intuitively, because emissions are proportional to output, a given degree of abatement will have a smaller effect on emissions the lower is the level of output. This effect on marginal benefit of abatement is offset to some degree by the higher externality cost of marginal emissions (i.e. the carbon price) which raises the marginal benefit of abatement. The simulations reveal that the net effect on marginal benefit is negative (for the Low relative to Medium demographic scenario but much less so for the Medium relative to High scenario). Both of these effects – higher marginal cost and lower marginal benefit – result in a lower level of abatement. Again, this is borne out in the simulations.

The above explanation of the effects of lower fertility on the carbon price and carbon abatement is illustrated diagrammatically in Figure 2a. The carbon price is measured on the vertical axis and the optimal abatement expenditure is illustrated on the horizontal axis. The Low scenario gives a higher marginal cost (MC) schedule and a lower marginal benefit (MB) schedule, the net effect of which is a lower abatement level and a higher carbon price.

Figure 2b accompanies Figure 2a in order to show the implications of the optimal carbon price on a market for carbon permits. The schedules $D_{MED}$ and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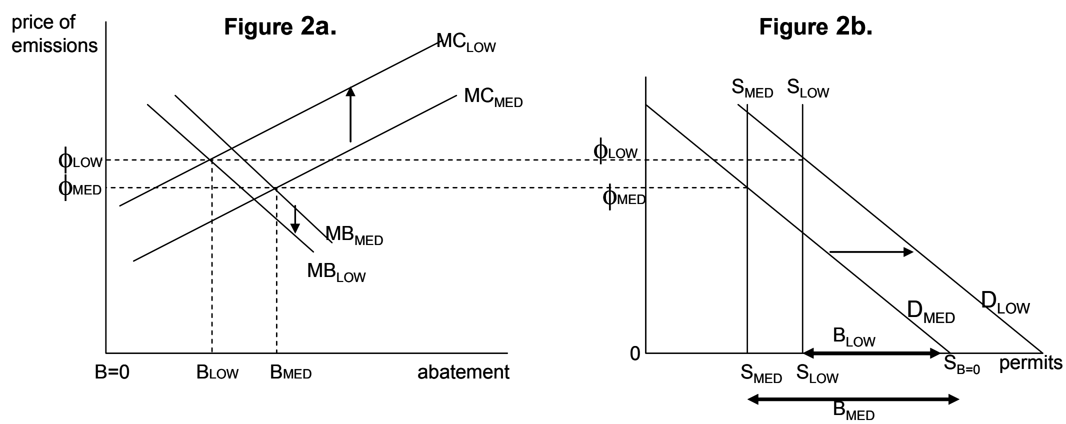
$D_{LOW}$ are the demand for carbon permits under the Med and Low scenarios. The demand for permits is determined by the cost of abatement. Firms will abate as long as the cost of abating is less than the cost of not abating – that is, of emitting - which is the price of a permit required to emit. At a permit price of zero, for example, the price of emitting is zero and therefore there is no abatement ($B=0$) and the optimal demand (and supply) for permits is equal to $S_{B=0}$. At an optimal carbon price of $\phi_{MED}$ the optimal demand (and supply) of permits is $S_{MED}$ which is achieved by the government issuing permits of that quantity. The Low scenario shifts the marginal cost of abatement upward which reduces the quantity of permits demanded at any price. Hence the demand for permits shifts to the right when the demographic scenario shifts from Med to Low. In the Low scenario the optimal carbon price is $\phi_{LOW}$ , the optimal number of permits is $S_{LOW}$ , which implies the need for the government to increase the supply of permits to $S_{LOW}$.

The simulations reported below aim to determine the order of magnitude of the effects of the three demographic scenarios on the paths of the optimal carbon price, optimal emissions and optimal abatement.

**Figure 2. Effect of low fertility on carbon price and abatement**




# 4 Simulation Results

The first simulation is a “business as usual” (BAS) simulation where abatement is zero in all periods. This simulation is then compared with the optimal abatement simulation in order to see the effect of optimal abatement on emissions for the baseline parameter values. The Medium demographic scenario is adopted in both cases. Figure 3 plots the resulting paths for the stock of emissions, $S_t$. In the BAS case the stock of emissions doubles from the year 2005 to the year 2150, whereas in the optimal abatement scenario the stock of emissions increases by only 10 percent by 2050 after which the stock of emissions slowly falls back to its initial level by 2150. This is achieved with optimal abatement starting at 1 percent of GDP and then increasing gradually until it is 3 percent of GDP by 2150. (See the Appendix for details of calibration such that optimal abatement starts at 1 percent of GDP.)

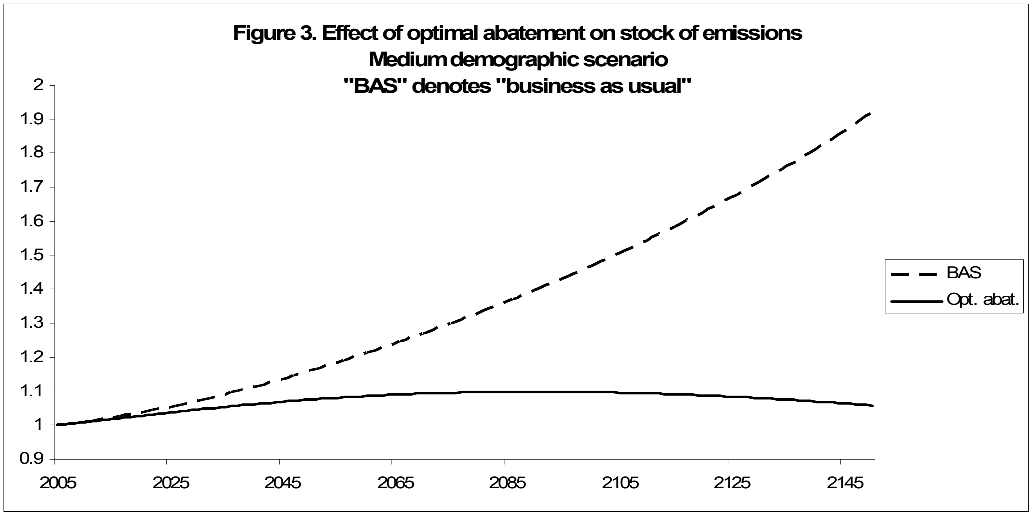



Figure 4 plots the stock of emissions, $S_t$, under the three demographic scenarios under optimal abatement in each case. By the year 2050 the stock of emissions in the Low scenario is 5 percent below the stock of emissions in the Medium scenario which is itself 7 percent below the stock in the High scenario. Emissions are ultimately lower the lower is the fertility rate, mainly due to lower output as discussed above.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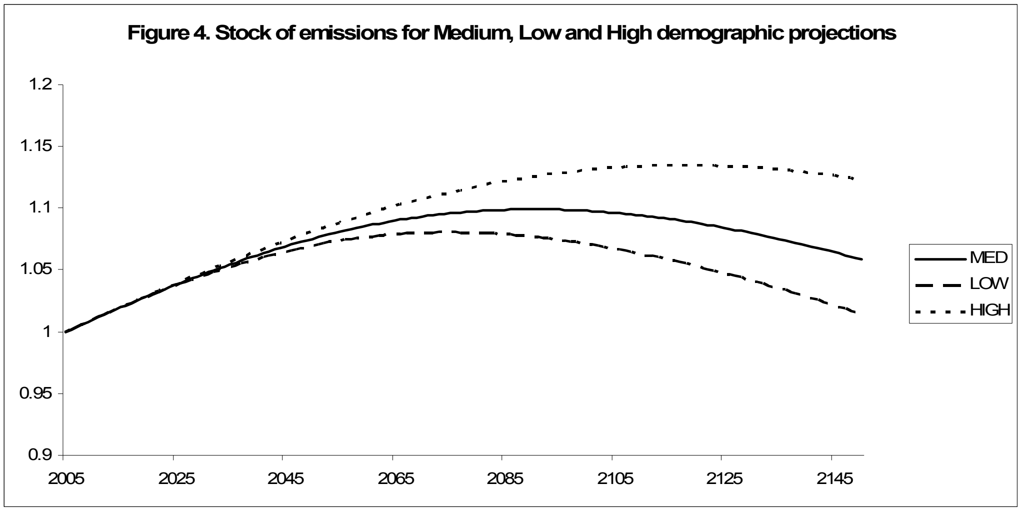
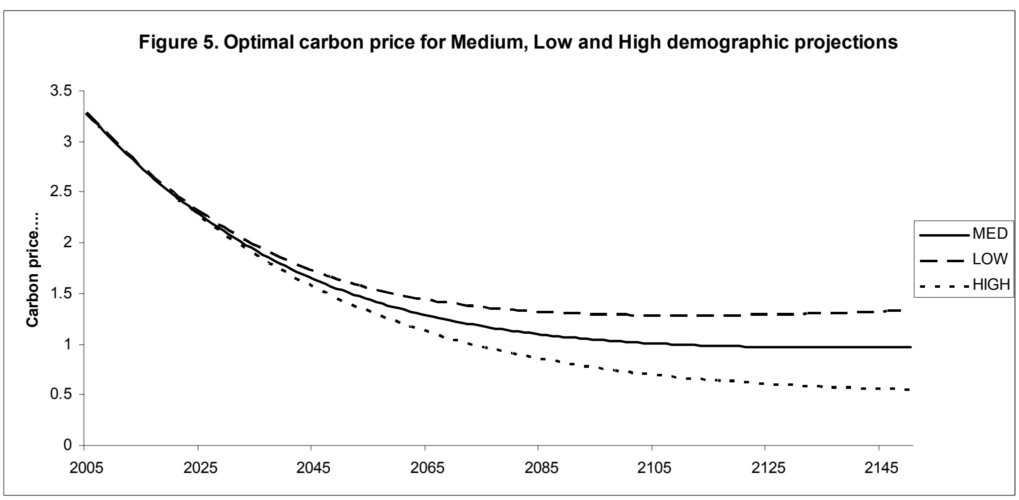


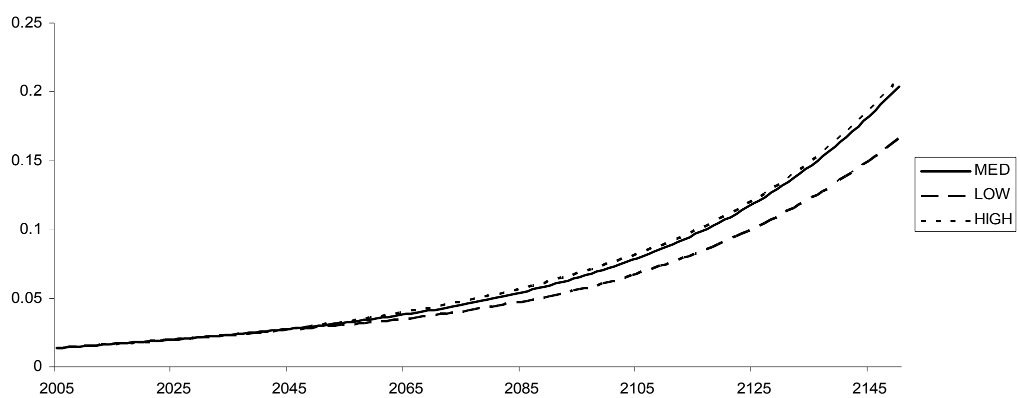

The effect of demographic change on the optimal carbon price is plotted in Figure 5. The intuition explained above is borne out. In the Low scenario the optimal carbon price gradually rises above that in the Medium scenario such that the price is nearly 40 percent higher by the year 2150. Similarly the price in the

High scenario is more than 40 percent below the price in the Medium scenario. The difference between the Low and High scenarios is therefore significant – the Low scenario yields an optimal carbon price more than double that under the High scenario.




The corresponding levels of abatement expenditure for the three scenarios are plotted in Figure 6. Again consistent with the discussion above, abatement is clearly lower in the Low scenario relative to the other scenarios; but abatement is only very slightly lower – imperceptibly almost – in the Medium scenario relative to the High scenario. The reason for the latter can be traced to the effects on the marginal benefit of abatement. The High scenario results in a lower externality cost of abatement (carbon price) but higher output, which have opposite effects on the marginal benefit of abatement. The effect of the lower carbon price dominates resulting in a lower marginal benefit. This tends to lower optimal abatement and offsets the effect of lower marginal cost in raising optimal abatement. The net effect is a very slightly higher degree of optimal abatement in the High scenario relative to the Medium scenario. This is the sort of result that demands sensitivity testing which is reported in the Appendix.

**Figure 6. Optimal abatement for Medium, Low and High demographic projections.**




# 5 Policy Implications and Caveats

The analysis in this paper suggests a public policy trade-off to some extent between mitigating population ageing and mitigating climate change. The low fertility scenario, which leads to an older future population, results in lower carbon emissions. This in turn implies a lower degree of optimal carbon abatement and therefore a lower optimal carbon price. In this sense, population ageing is itself a carbon abatement mechanism. The implication is that policies to mitigate population ageing, such as boosting the fertility rate and increasing the labour force participation rate of older workers, may lead to higher carbon emissions and therefore require a greater policy effort in reducing carbon emissions.

At the very least the results suggest that global demographic change may have a non-trivial impact on the optimal carbon price, the path of emissions and optimal abatement expenditure. The Low and High demographic scenarios result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in a carbon price that deviates from that under the Medium scenario by some 15% by 2050 and 40% by 2150.

The advantage of applying a simple Ramsey model is that the forces driving the optimal carbon price, and the impact of demographic change on those forces, are transparent. The main channels through which demographic change affects the carbon price are the marginal damage function and the marginal product of capital, along with the level of output as a scale variable. Even in such a simple model, these channels were shown to depend on the interaction of a number of parameters. However, the usual caveats apply in simulating such a highly aggregated model so far into the future. The sacrifice that comes with parsimony is the neglect of some channels through which demographic change could affect the optimal carbon price. For example, a simple Ramsey model cannot deal with substitution by firms among technologies with different energy intensities, nor substitution by consumers among goods with different energy intensities; also, the assumption of perfect foresight rules out the effect of uncertainty and of the impact of future catastrophic events which have low probability but would cause substantial damage. These caveats should be borne in mind in interpreting the policy trade-off suggested by the results here.

# Appendix A. Appendix. Parameter Values and Sensitivity Analysis

The model is calibrated in order to generate paths (under the Medium demographic scenario) for the stock of emissions and the cost of abatement that are fairly close to those in Stern (2007) while at the same time maintaining faith with standard assumptions in applied Ramsey models. In some cases parameter values are adopted directly from Stern (2007). An exception is the rate of time preference for which the value in Stern has been widely criticised for being too low, and more importantly, inconsistent with the value of the elasticity of marginal utility. The baseline value of the rate of time preference here is somewhat higher than that in Stern, but Stern’s value is simulated as part of the sensitivity analysis. The baseline parameter values are given in Table A1.

Table A2 gives the values at 2005, 2050, 2100 and 2150 for three variables: the optimal carbon price, $\phi_t$, the stock of emissions, $S_t$, and the abatement expenditure, $B_t$, for an alternative value of each of the key parameters and for each of the three demographic projections. The sensitivity analysis aims to answer two questions: (i) given a particular demographic scenario, are the outcomes for the carbon price, emissions and abatement expenditure sensitive to alternative parameter values? (ii) to what extent does the impact of alternative demographic scenarios depend on the parameter values?

The rate of time preference and elasticity of marginal utility are simulated in combination in Table A2, since they are related in determining an initial pre-emissions steady state and also in terms of their inferences about equity (see discussion in the Appendix). The first alternative combination of these two parameters in Table 1 consists of Stern's value of $\theta$: $\theta$=0.001, and the value of $\beta$ that is consistent with the initial steady state, giving $\beta$=3.75 which is higher than Stern's value of $\beta$=1. The effect on the carbon price path is not qualitatively different from the base case (see Table A2). The second combination of $\beta$ and $\theta$ in Table A2 represents intermediate values of the two parameters. Again there is little qualitative impact on the path of the carbon price. The same can be said for the effects of these parameters on the stock of emissions and the level of abatement – there are some material quantitative effects but the qualitative effects are trivial. The other parameters listed above have the expected effects on the carbon price path, discussed in Section 2.

The second question concerns the effect of demographic assumptions under alternative parameter values. Under the baseline parameter values, the Low and High scenarios result in a deviation of the optimal carbon price by some 15% by 2050 and 40% by 2150, relative to the Medium scenario.

Table A1. Baseline parameter values

| | |
|---|---|
| Time preference rate, $\rho$ | 0.029 |
| Elasticity of marginal utility, $\beta$ | 1.0 |
| Elasticity of emissions with respect to output, $\omega$ | 0.8 |
| Elasticity of emissions with respect to abatement, $\sigma$ | 1.0 |
| Emissions shock parameter, $\mu$ | 0.00004 |
| Rate of natural absorption of pollution, $\varepsilon$ | 0.005 |
| Elasticity of output with respect to emissions stock, $\eta$ | 0.05 |
| Capital elasticity of output, $\gamma$ | 0.25 |
| Initial capital to output ratio, $(K/Y)_0$ | 3.0 |
| Depreciation rate, $\delta$ | 0.05 |
| Total factor productivity growth, (growth rate of $A_t$ ) | 0.01 |
| Time horizon, $T$ | 200 |


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**Table A2. Sensitivity analysis**

| | | | | Demographic projections | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | MED | LOW | HIGH | MED | LOW | HIGH | MED | LOW | HIGH |
| | | | | *Carbon price, $\phi_t$* | | | *Stock of emissions, $S_t$* | | | *Abatement, $B_t$* | | |
| **Baseline values of all parameters** | | | | | | | | | | | | |
| | | | 2005 | 3.278 | 3.289 | 3.269 | 1.000 | 1.000 | 1.000 | 0.014 | 0.014 | 0.014 |
| | | | 2050 | 1.530 | 1.627 | 1.431 | 1.075 | 1.070 | 1.081 | 0.030 | 0.029 | 0.030 |
| | | | 2100 | 1.023 | 1.289 | 0.729 | 1.098 | 1.071 | 1.131 | 0.072 | 0.062 | 0.075 |
| | | | 2150 | 0.972 | 1.333 | 0.554 | 1.059 | 1.015 | 1.123 | 0.204 | 0.166 | 0.209 |
| **Sensitivity with respect to:** | | | | | | | | | | | | |
| | **Baseline** | **Alternative** | | | | | | | | | | |
| ρ and β | ρ=0.029 | ρ=0.001 | 2005 | 2.681 | 2.713 | 2.652 | 1.000 | 1.000 | 1.000 | 0.014 | 0.014 | 0.014 |
| | β=1 | β=3.75 | 2050 | 1.226 | 1.327 | 1.120 | 1.078 | 1.071 | 1.084 | 0.029 | 0.028 | 0.029 |
| | | | 2100 | 0.734 | 0.937 | 0.503 | 1.114 | 1.091 | 1.147 | 0.060 | 0.047 | 0.065 |
| | | | 2150 | 0.630 | 0.906 | 0.305 | 1.094 | 1.053 | 1.167 | 0.145 | 0.109 | 0.148 |
| ρ and β | | ρ=0.01 | 2005 | 2.980 | 3.001 | 2.931 | 1.000 | 1.000 | 1.000 | 0.014 | 0.014 | 0.014 |
| | | β=2 | 2050 | 1.220 | 1.334 | 1.216 | 1.088 | 1.081 | 1.086 | 0.025 | 0.025 | 0.029 |
| | | | 2100 | 0.447 | 0.753 | 0.486 | 1.175 | 1.129 | 1.159 | 0.037 | 0.035 | 0.059 |
| | | | 2150 | 0.191 | 0.635 | 0.246 | 1.238 | 1.117 | 1.198 | 0.057 | 0.069 | 0.122 |
| σ | 1 | 0.5 | 2005 | 6.623 | 6.645 | 6.605 | 1.000 | 1.000 | 1.000 | 0.014 | 0.014 | 0.014 |
| | | | 2050 | 5.211 | 5.320 | 5.102 | 1.083 | 1.078 | 1.089 | 0.054 | 0.050 | 0.057 |
| | | | 2100 | 5.113 | 5.389 | 4.811 | 1.125 | 1.095 | 1.157 | 0.218 | 0.157 | 0.279 |
| | | | 2150 | 5.412 | 5.875 | 5.086 | 1.114 | 1.058 | 1.178 | 0.866 | 0.529 | 1.276 |
| ε | 0.005 | 0.01 | 2005 | 3.278 | 3.289 | 3.269 | 1.000 | 1.000 | 1.000 | 0.014 | 0.014 | 0.014 |
| | | | 2050 | 2.208 | 2.346 | 2.068 | 0.760 | 0.755 | 0.764 | 0.036 | 0.035 | 0.037 |
| | | | 2100 | 2.253 | 2.809 | 1.642 | 0.536 | 0.520 | 0.555 | 0.110 | 0.094 | 0.116 |
| | | | 2150 | 3.246 | 4.362 | 1.964 | 0.356 | 0.337 | 0.384 | 0.386 | 0.306 | 0.410 |
| ω | 0.8 | 0.5 | 2005 | 3.278 | 3.289 | 3.269 | 1.000 | 1.000 | 1.000 | 0.014 | 0.014 | 0.014 |
| | | | 2050 | 1.521 | 1.619 | 1.499 | 1.066 | 1.062 | 1.067 | 0.027 | 0.027 | 0.026 |
| | | | 2100 | 1.002 | 1.273 | 0.724 | 1.073 | 1.055 | 1.095 | 0.060 | 0.056 | 0.055 |
| | | | 2150 | 0.944 | 1.312 | 0.519 | 1.025 | 0.996 | 1.071 | 0.161 | 0.149 | 0.137 |
| η | 0.05 | 0.02 | 2005 | 3.318 | 3.329 | 3.309 | 1.000 | 1.000 | 1.000 | 0.014 | 0.014 | 0.014 |
| | | | 2050 | 2.804 | 2.850 | 2.757 | 1.054 | 1.050 | 1.057 | 0.040 | 0.038 | 0.042 |
| | | | 2100 | 2.822 | 2.940 | 2.692 | 1.036 | 1.023 | 1.051 | 0.119 | 0.093 | 0.143 |
| | | | 2150 | 3.051 | 3.211 | 2.865 | 0.976 | 0.955 | 0.999 | 0.356 | 0.252 | 0.470 |
| δ | 0.05 | 0.02 | 2005 | 3.027 | 3.036 | 3.020 | 1.000 | 1.000 | 1.000 | 0.014 | 0.014 | 0.014 |
| | | | 2050 | 2.133 | 2.177 | 2.090 | 1.023 | 1.021 | 1.026 | 0.073 | 0.069 | 0.076 |
| | | | 2100 | 2.257 | 2.327 | 2.183 | 0.959 | 0.952 | 0.965 | 0.461 | 0.352 | 0.565 |
| | | | 2150 | 2.489 | 2.569 | 2.404 | 0.875 | 0.868 | 0.882 | 2.444 | 1.494 | 3.563 |
| γ | 0.25 | 0.3 | 2005 | 3.341 | 3.352 | 3.331 | 1.000 | 1.000 | 1.000 | 0.015 | 0.015 | 0.015 |
| | | | 2050 | 2.369 | 2.177 | 2.047 | 1.034 | 1.036 | 1.043 | 0.032 | 0.056 | 0.061 |
| | | | 2100 | 2.110 | 2.233 | 1.978 | 0.992 | 0.983 | 1.003 | 0.271 | 0.212 | 0.326 |
| | | | 2150 | 2.310 | 2.455 | 2.151 | 0.913 | 0.901 | 0.926 | 1.221 | 0.821 | 1.659 |

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