The Leverage of Demographic Dynamics on Carbon Dioxide Emissions. Does Age Structure Matter?*

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Abstract

The paper formally discusses the impact of demographic dynamics on carbon dioxide emissions and empirically investigates the effect of population aging on carbon dioxide emissions for the United States. First, a generalization of the IPAT equation within the framework of input-output economic models is presented. A formal analysis of the impact of changes in mortality and fertility schedules on carbon dioxide emissions is offered within the context of stable population theory and the Solow model of economic growth. Second, demographic rates and expenditure data for the United States are used to parameterize the formal model. A new methodology to estimate consumption profiles of goods by age, given data on household expenditures, is described. Estimated consumption profiles for several energy-intensive goods are then used as input for the formal model. Empirical evidence for the United States shows that changing population age structure, and in particular population aging, may have a noticeable positive effect on carbon dioxide emissions in the next few decades.

INTRODUCTION

In 1970 the U.S. Commission on Population Growth and the American Future asked the research organization ‘Resources for the Future’ to undertake a project to identify the principal resource and environmental consequences of future population growth in the United States. Two years later, the results of the research were published in the volume ‘Population, Resources, and the Environment’ (1972), edited by Ronald Ridker. The project represented an important attempt to assess the environmental consequences of demographic, economic and technological dynamics, based on input-output economic tables (Herzog and Ridker 1972; Ridker 1972).

In addition to that, the volume featured a piece by Commoner (1972) and one by Ehrlich and Holdren (1972) which helped to operationalize the IPAT equation (Ehrlich and Holdren 1971), an accounting identity that decomposes environmental impact (I) into the product of population size (P), affluence (A) and technology (T):

$$I = P \times A \times T \tag{1}$$

Affluence is intended as per-capita income (Y/P) and technology is expressed as environmental impact per unit of economic production (I/Y).

The IPAT equation has strongly influenced research carried out by demographers on the impact of population growth on greenhouse gases emissions (Pebley 1998) and it has inspired several macrodecomposition analyses (e.g., Dietz and Rosa 1997; MacKellar, Lutz, Prinz and Goujon 1995; O’Neill, MacKellar and Lutz 2001; Preston 1996; York, Rosa and Dietz 2003; Zagheni and Billari 2007).

Conversely, the seminal demographic work based on economic input-output tables proposed by Ridker and colleagues (e.g., Herzog and Ridker 1972; Ridker 1972) has not influenced the future work of demographers on greenhouse gases emissions as much as the IPAT equation.

Recently, the traditional framework of economic input-output analysis (e.g. Leontief 1953, 1970, 1986), applied to environmental problems, has received some attention in the field of environmental engineering. In particular, several techniques have been developed in the context of life cycle assessment to evaluate the environmental impact of alternative economic choices, when the entire supply chain of requirements is taken into consideration (Hendrickson, Lave and Matthews 2006).

This paper supplements traditional economic input-output approaches (e.g., Leontief 1953, 1970, 1986; Herzog and Ridker 1972) with recent developments in life cycle analysis methods (Hendrickson et al. 2006) and a well grounded theory of population, such as the stable population theory (e.g., Keyfitz and Caswell 2005).

Methodologically, I integrate input-output models with a demographic component and I present a generalization of the IPAT equation to a multi-sector economy with an age-structured population. I then use this conceptual framework, together with tools developed in the context of stable population theory, to get insights on the leverage of changing mortality and fertility patterns on carbon dioxide emissions.

Empirically, I estimate age-specific consumption profiles for a set of energy-intensive goods. These estimates are then used as inputs for the theoretical model. Age-specific expenditure on consumption goods is a key link between demographic dynamics and their environmental consequences (e.g., Pebley 1998). In the empirical section of the paper I propose a statistical model of household consumption as a function of its size and age structure. First, I use the model to estimate expenditure profiles by age and the extent of economies of scale in household consumption. Second, I estimate variations in carbon dioxide emissions associated to changes in population growth and age structure, based on the input-output model and the estimated age-specific consumption profiles.

Demographic trends and changes in economic production are the main factors driving greenhouse gases emissions (e.g., O'Neill, MacKellar and Lutz, 2001), which, in turn, are most likely responsible for the observed increase in average global temperatures (IPCC, 2007). This paper gives a contribution to our understanding of the mechanisms through which demographic dynamics affect the level of carbon emissions and, thus, climate change.

THE THEORETICAL MODEL

This section is dedicated to the formal discussion of the conceptual scheme that I use throughout the paper to analyze the impact of demographic dynamics on the environment. In particular, I model a set of ‘environmental burdens’, of which carbon dioxide emissions is central for our purposes, as a function of demographic, economic and technological variables. I develop a model that combines tools from economics, statistics and mathematical demography. The age structure of a population plays an important role in the explanation of levels of environmental burdens. Changes in age structure have an effect on the environment mediated by levels of per capita consumption, existing technology and the structure of the economy.

In this section, I set the foundation for the statistical analysis that I develop in the following sections, where I estimate, among others, consumption profiles by age for several energy-intensive consumption goods. To be consistent with the following sections and the empirical analysis, I present the model in discrete terms, although a continuous version of the model may be easier to read and more elegant.

The first subsection describes the model that will be used throughout the paper. The second subsection formalizes the role of demographic and economic change on the level of environmental burdens. I will consider, for instance, the quantitative impact of changes in mortality and fertility rates on the growth rate and age structure of a stable population, and their consequences on carbon dioxide emissions.

The input-output approach

The input-output approach to model the economy and its environmental requirements dates back to the pioneering work of Leontief (1953, 1970, 1986). In what follows I briefly give a representation of an input-output model, as it appears in Hendrickson et al. (2006), and I introduce the role of demography within an input-output framework.

Consider an economy with m sectors, indexed by i. The total monetary output for sector i, y_i, is written as:

$$y_i = z_{i1} + z_{i2} + \cdots + z_{im} + d_i \tag{2}$$

where z_{ij} is the monetary flow of goods from sector i to sector j and d_i is the final demand for the good i. The model is typically rewritten to represent the flows between sectors as a percentage of sectoral output. Thus, if we write:

$$q_{ij} = \frac{z_{ij}}{y_j}$$

the model is expressed as:

$$y_i = q_{i1}y_1 + q_{i2}y_2 + \cdots + q_{im}y_m + d_i \tag{3}$$

or, equivalently:

$$-q_{i1}y_1 - q_{i2}y_2 - \cdots + (1 - q_{ii})y_i - \cdots - q_{im}y_m = d_i \tag{4}$$

By letting Q be the $m \times m$ matrix containing all the coefficients q_{ij}, Y the $m \times 1$ vector containing all the output y_i terms, and D the $m \times 1$ vector of final demands d_i, the model is written in a more compact form as:

$$[I - Q]Y = D \tag{5}$$

This way, given the vector of final demands, and the matrix of coefficients Q, the vector of outputs by sector is obtained as:

$$Y = [I - Q]^{-1}D \tag{6}$$

Hendrickson et al. (2006) make use of this model to evaluate human environmental impact. In particular, they provide estimates for a set of coefficients that transform monetary economic output of each sector into ‘environmental burdens’. They use the term ‘environmental burden’ to indicate a wide range of factors that affect the environment, such as toxic emission, air pollution, greenhouse gases emissions. For this paper, I use the expression 'environmental burden' as a synonym for carbon dioxide emission.

Let R be a $m \times m$ matrix with diagonal elements representing the impact per dollar of output for each stage of production and B the $m \times 1$ vector of environmental burdens for each production sector. Then:

$$B = RY = R[I - Q]^{-1}D \tag{7}$$

I analyze the role of demographic factors within the conceptual framework described in equation 7. In particular, I represent the vector of final demands as the product of age-specific consumption profiles and population size by age groups:

$$D = CK \tag{8}$$

where C is a $m \times s$ matrix whose row i represents the profile of average consumption by age group for the output produced in sector i. K is a $s \times 1$ vector of population sizes for the s age groups considered.

By plugging expression 8 into equation 7, we obtain:

$$B = R[I - Q]^{-1}CK \tag{9}$$

Equation 9 represents the model that I suggest to analyze the impact of demographic changes on environmental burdens. It is the core of my analysis and it gives the main motivation for the empirical investigation that follows. The purpose of the empirical analysis is to estimate consumption profiles by age for energy-intensive consumption goods. Given such estimates, we can evaluate the effect of changes in population age structure on final demands for consumption goods and associated environmental burdens.

We can interpret the model that I suggest as a generalization of the well-known IPAT equation (Ehrlich and Holdren 1971, 1972; Commoner 1972), that simply states that environmental impact (I) is the product of population size (P), affluence (A), and technology (T). In the input-output model, B is the environmental impact, which corresponds to I. K has the role of P, that is the demographic factor. C is the level of affluence, or A in the IPAT terminology. C depicts the level of consumption for the population and it is 'weighted' by $[I-Q]^{-1}$ to differentiate consumption according to the sectors of the economy to which we can impute the production of the final goods. Finally, R is the term that is analogous to T and represents the 'impact' per unit of production in each sector. We thus may think of the model that I propose as a generalization of the IPAT equation to a multi-sector economy and age-structured population. When we consider an economy with only one sector and we ignore the population age structure, the model reduces to the one depicted by the IPAT equation.

The leverage of a change in mortality and fertility

In this subsection, I try to get some insights on the effects of demographic and economic dynamics on carbon dioxide emissions, within the framework of stable population theory (e.g., Keyfitz and Caswell 2005), the Solow model of economic growth (Solow 1956), and the input-output approach described in the previous section. I focus on two important aspects of the impact of demographic factors on environmental burdens: population growth and age structure. Classic models of economic growth such as the Solow model emphasize the role of population growth on economic growth. The approach based on the input-output model provides some insights on the role of population age structure.

An economy described by the Solow model tends to converge over time to a steady-state growth path such that:

$$\frac{\dot{Y}_t}{Y_t} = \frac{g}{1-\alpha} + r \tag{10}$$

Equation 10 means that the output growth rate ($\dot{Y}_t/Y_t$) of the economy is determined by the rate of technological progress (g), the growth rate of the labor force (r), and a factor controlling for the extent of diminishing marginal returns to capital (α).

If we assume that the shape of per-capita consumption profiles by age is constant over time, but the level of consumption profiles grows with technological progress, then the growth rate of per-capita consumption over time is $(\frac{g}{1-\alpha})$, with population growing at a rate r.

By explicitly incorporating these assumptions into the model based on the input-output approach, as it appears in equation 9, we find that the vector of environmental burdens, B, grows at the same rate as the economic output:

$$\frac{\dot{B}_t}{B_t} = \frac{g}{1-\alpha} + r \tag{11}$$

Within this framework, population growth induces higher levels of production and consumption which, in turn, have an adverse effect on the environment, by increasing the growth rate of environmental burdens.

Now, since we are considering a population with stable age structure, the population and labor force growth rate, r, can be linearly approximated to:

$$r \approx \frac{\ln{(NRR)}}{a_f} \tag{12}$$

where NRR is the net reproduction ratio and a_f is the mean age at childbearing.

By plugging equation 12 into 11 and expressing the NRR in terms of its components, the growth rate of environmental burdens becomes:

$$\frac{\dot{B}_t}{B_t} \approx \frac{g}{1-\alpha} + \frac{\ln(p(a_f) \times F \times f_{fab})}{a_f} \tag{13}$$

where F is the total fertility rate, f_{fab} is the fraction of females at birth and $p(a_f)$ is the proportion of female births surviving to the mean age at childbearing.

Equation 13 explicitly links demographic factors such as survivorship, fertility and mean age at childbearing, to the growth rate of the specific environmental burden considered. Thus, we isolate the leverage of each demographic factor on the growth rate of the environmental burden.

A formal discussion of the effect of changes of fertility and mortality schedules on the growth rate of a stable population is based on a long history of mathematical thought. Keyfitz and Caswell (2005) and Lee (1994) give a very good summary of the main results in this context and discuss the study of the formal demography of aging. The approach that is described in Lee (1994) can be applied to our case to evaluate the effect of a change in mortality, indexed by i, on the growth rate of an environmental burden:

$$\frac{\partial \frac{\dot{B}_t}{B_t}}{\partial i} \approx \frac{\partial p(a_f)/\partial i}{p(a_f) \times a_f} \tag{14}$$

The impact of a change in mortality on population growth is independent of the level of fertility: mortality decline, for instance, is associated with increasing $p(x)$. The effect on the age distribution is ambiguous, though. At the individual level, people live longer and thus the population gets older. At the population level, lower mortality means also that more women survive to childbearing age. This translates into more births and thus tends to make the population younger.

The proportion of people in each age group is a relevant variable for our purposes. As a matter of fact, given a per-capita consumption profile by age for a specific good, the age distribution of the population may have a relevant impact on the overall level of consumption of the good.

When we consider fertility in a stable population, we observe that changes in fertility schedules affect the rate of growth of a population, r, but not the probability of survivorship, $p(x)$. In terms of age structure, higher fertility is associated with increasing size of more recently born cohorts, relative to older ones, and it thus makes the population younger. Formally:

$$\frac{\partial \frac{\dot{B}_t}{B_t}}{\partial F} \approx \frac{1}{F \times a_f} \tag{15}$$

The age structure of the population plays an important role in our model of environmental burdens: given an age profile of consumption, the age structure determines the level of environmental burdens. Personal expenditure on different consumption goods is one of the key links between changes in demographic characteristics and the resource and environmental consequences of these changes. The development of a statistical model of household consumption as a function of household size and age structure is thus central to our purposes and will be discussed in the next section. Estimates of consumption patterns by age will then be used to evaluate changes in energy requirements and carbon dioxide emissions associated to changes in age structure.

DATA AND METHODS

Data

The empirical analysis focuses on the United States and is based on data from the Consumer Expenditure Survey (CES) 2003, provided by the Bureau of Labor Statistics of the U.S. Department of Labor. CES is a nationally representative survey that provides data on household expenditures for several consumption goods and services in the United States. Demographic and economic data for households units are also gathered. The data are collected in independent quarterly interviews and weekly diary surveys of approximately 7,000 sample households. Each survey has its own independent sample, and collects data on household income and socio-economic characteristics. The interview survey includes monthly out-of-pocket expenditures such as housing, apparel, transportation, health care, insurance, and entertainment. The diary survey includes weekly expenditures of frequently purchased items such as food and beverages, tobacco, personal care products, and nonprescription drugs and supplies. The two data sources are then integrated into one data set.

CES provides a lot of information on household consumption expenditure of energy-intensive goods, whose production accounts for a large part of carbon dioxide emissions. For this analysis I focus on the following consumption goods: electricity, natural gas, gasoline, air flights, tobacco products and number of vehicles owned.

Estimation of consumption patterns by age

Given data on consumption of several items by household units, a first goal is to assign to each member of the household his/her own share of consumption (in monetary terms). I also would like to estimate the extent of economies of scale and to separate the income effects from purely demographic effects.

In the literature, Mankiw and Weil (1989) faced a similar problem in the context of modeling demand for housing: they suggest to model household consumption of goods and services as an additive function of the consumption of its members. In what follows, I first discuss Mankiw and Weil (1989) approach applied to our case. Then I propose a new method based on the use of an equivalence scale.

Let c_{ij} be the consumption of good i by household j. Then,

$$c_{ij} = \sum_{k=1}^{M} c_{ijk} \tag{16}$$

where c_{ijk} is the demand of the kth member and M is the total number of people in the household.

The consumption of the good i for each individual is a function of age: each age has its own consumption parameter, so that an individual demand is given by:

$$c_{ijk} = \beta_0 Ind(0)_k + \beta_1 Ind(1)_k + \cdots + \beta_{80} Ind(80)_k \tag{17}$$

where:

$$Ind(h)_k = \begin{cases} 1 & \text{if age of member k is equal to h} \\ 0 & \text{otherwise} \end{cases}$$

The parameter β_h is the demand for consumption of a person of age h. Combining equation 16 with 17 we obtain the equation for consumption of good i by household j:

$$c_{ij} = \beta_0 \sum_k Ind(0)_k + \beta_1 \sum_k Ind(1)_k + \cdots + \beta_{80} \sum_k Ind(80)_k \tag{18}$$

The parameters of equation 18 are estimated by using the least squares technique. After appropriately smoothing (e.g., Friedman, 1984) the sequence of estimated parameters over age, we get an age profile of demand for consumption good i. This age-specific schedule of consumption can be interpreted as the impact of an additional person of a particular age on expenditure on a specific good.

If we want to separate the effect of age from the one of income, we can use the same method applied to fraction of household expenditures, instead of overall consumption.

To the extent that there are not economies of scale in household consumption (or they are negligible) and to the extent that household formation is fairly constant, this approach is fairly accurate (Mankiw and Weil 1989). However, economies of scale may be relevant in our case and we want to be able to evaluate them with a statistical model and to estimate consumption profiles by age accordingly.

I address the problem of evaluating the importance of economies of scale by suggesting a parametric equivalence scale that takes into account that children consume less than adults and that living arrangements with more than one person may be more efficient. In what follows, I present the model that I suggest and the strategy that I propose to estimate its parameters and the consumption profiles.

Let n_{cj}, n_{aj}, n_{ej} be, respectively, the number of children, adults and elderly that live in household j, where we define children those people whose age is between 0 and 14 years, adults those between 15 and 64 and elderly those whose age is 65 and over. Let S_{ia} and S_{ie} be respectively the average consumption of good i by adults and elderly who live alone. Then we can write an equivalence scale as:

$$c_{ij} = (n_{cj}\gamma_i S_{ia} + n_{aj} S_{ia} + n_{ej} S_{ie})^{\theta_i} + \epsilon_j \tag{19}$$

where γ_i is a parameter that represents the relative consumption of children, with respect to adults, within households. $\gamma_i = 0$ means that only adults are considered responsible for the consumption of the good i; $\gamma_i = 1$ means that no distinction is made between adults and children in terms of consumption of the good i. θ_i is a parameter that represents the extent of economies of scale from cohabitation for the good i. $\theta_i < 1$ means that cohabitation generates economies of scale; $\theta_i > 1$ means that cohabitation generates diseconomies of scale. ϵ_j is an error term.

The equivalence scale suggested in equation 19 is a nonlinear model. I estimate the parameters γ_i and θ_i for the different consumption goods by using the least squares technique. Given the estimated values for S_{ia} and S_{ie}, we choose the pair ($\hat{\gamma_i}$, $\hat{\theta_i}$) such that:

$$(\hat{\gamma_i}, \hat{\theta_i}) = argmin_{\hat{\gamma_i}, \hat{\theta_i}} \sum_j \left(c_{ij} - (n_{cj}\gamma_i S_{ia} + n_{aj} S_{ia} + n_{ej} S_{ie})^{\theta_i}\right)^2 \tag{20}$$

Once we have estimates for the couple of parameters ($\hat{\gamma_i}$, $\hat{\theta_i}$), then we want to reconstruct a consumption profile by age based on the equivalence scale. In what follows I explain the strategy that I suggest. We need to estimate an extra parameter ψ_i that represents the relative consumption of good i by the elderly, with respect to adults, within a household j. We estimate this parameter as the mean relative consumption for the good i in the population of single-person households, that is $\hat{\psi_i} = \frac{S_{ie}}{S_{ia}}$. Then the equivalence scale becomes:

$$c_{ij} = \left(n_{cj}\hat{\gamma_i} cons_{ij} + n_{aj} cons_{ij} + n_{ej}\hat{\psi_i} cons_{ij}\right)^{\hat{\theta}_i} \tag{21}$$

where $cons_{ij}$ is the average consumption of good i by an adult in the household j. It can be retrieved as

$$cons_{ij} = \frac{c_{ij}^{(1/\hat{\theta}_i)}}{n_{cj}\hat{\gamma_i} + n_{aj} + n_{ej}\hat{\psi_i}} \tag{22}$$

Then, for the household j, the average consumption of a child will be $cons_{ij}\hat{\gamma_i}$ and the average consumption of an old person will be $cons_{ij}\hat{\psi_i}$. These two quantities represent the shares of consumption, for the good i, of children and elderly, respectively.

By applying the same procedures to all households in the data set, we get estimates of consumption by age for the goods considered. The average consumption profile by age is then obtained by taking the mean of these values by age and by appropriately smoothing (e.g., Friedman, 1984) them by age.

RESULTS

Age-specific consumption patterns

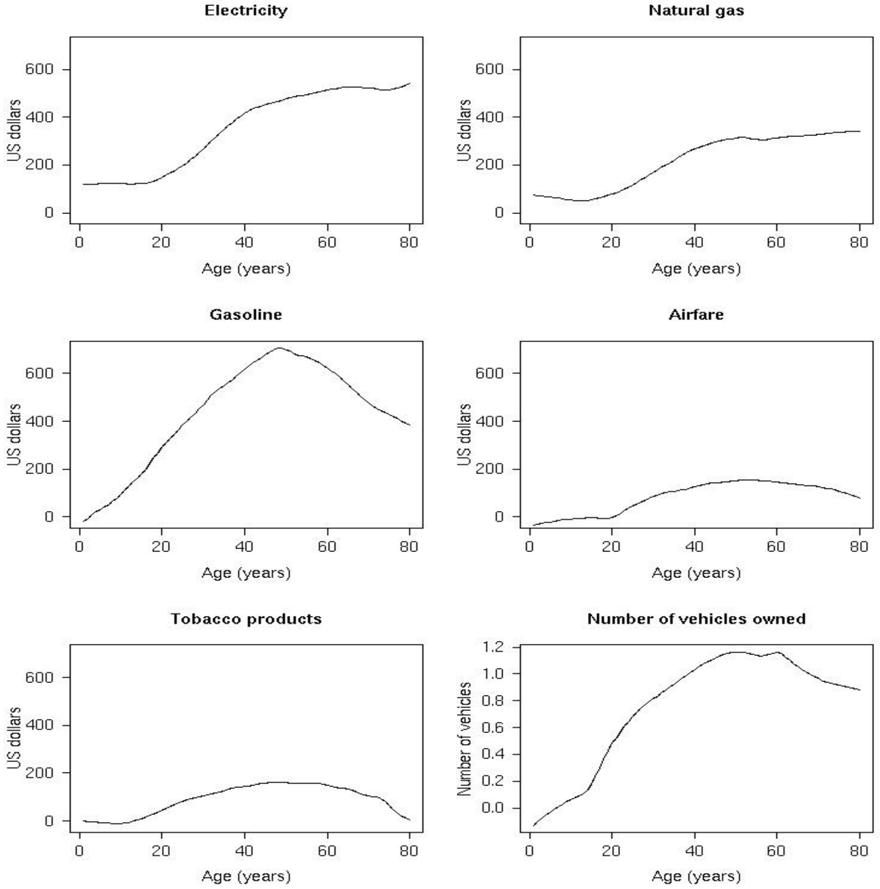
In this section, I present estimates of consumption profiles by age for a selected group of energy-intensive goods. Such estimates are obtained by applying the methods described in the previous section to U.S. expenditure data. These estimates show the role of a crucial demographic variable, such as age, on consumption of specific goods that have a relevant impact on carbon dioxide emissions.

Figure 1 shows estimates of age-specific demand for electricity, natural gas, gasoline, air flights, tobacco products and vehicles. These estimates are obtained by using the method suggested by Mankiw and Weil (1989) and they give the impact on demand of a specific good associated to the presence of an additional person, by age. Estimated values can be negative in some circumstances, meaning that the presence of a person of a particular age tends to reduce the household demand for the good. For instance, the presence of children in a household may have a negative impact on the number of cigarettes smoked by adults or the amount of money spent on air flights.

We observe that demand for the selected group of consumption goods tends to increase with age until the person reaches the adult life stage. For some goods such as electricity and natural gas, demand increases with age also for the elderly. For other goods, such as gasoline, air flights and number of vehicles owned, demand declines with age after the adult life stage. The observed life cycle consumption patterns could be related to specific preferences and characteristics that may vary over the life course: for instance, the ability and willingness to drive is strongly associated to age and may mediate the relationship between age and demand for gasoline. In addition to that, perhaps there is a cohort effect that plays a role in shaping the demand by age. For instance, the decrease in demand for gasoline and vehicles at older ages may be partially related to the specific circumstances experienced by older generations.

Some of the trends in demand for consumption goods by age may be driven by levels of income by age. To separate the income effect from the demographic effect on demand for consumption goods, I apply the method of Mankiw and Weil (1989) on fractions of expenditures on the specific goods. Figure 2 shows the estimated age-specific profiles of demand for the selected good. We observe that, although demand for air flights declines with age for the

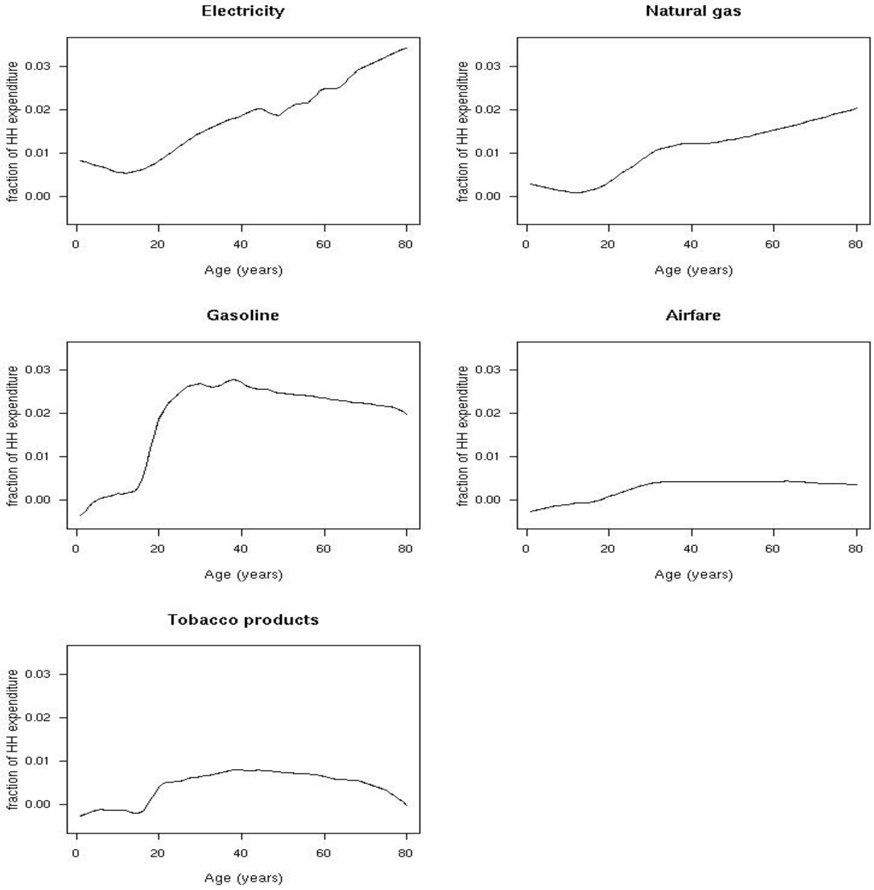
Figure 1: **U.S. profile of age-specific demand for consumption of a selected group of energy-intensive goods. Estimates are based on the approach suggested by Mankiw and Weil (1989).**



Data source: Consumer Expenditure Survey 2003.

elderly, the fraction of expenditures on air flights remains rather constant at old ages. As for energy demand, the profile of fraction of expenditures for electricity and natural gas at old ages is steeper than the respective profile of consumption. The opposite is true for gasoline. These observations are relevant to understand possible implications of changing levels of wealth for old people on their consumption of energy-intensive goods.

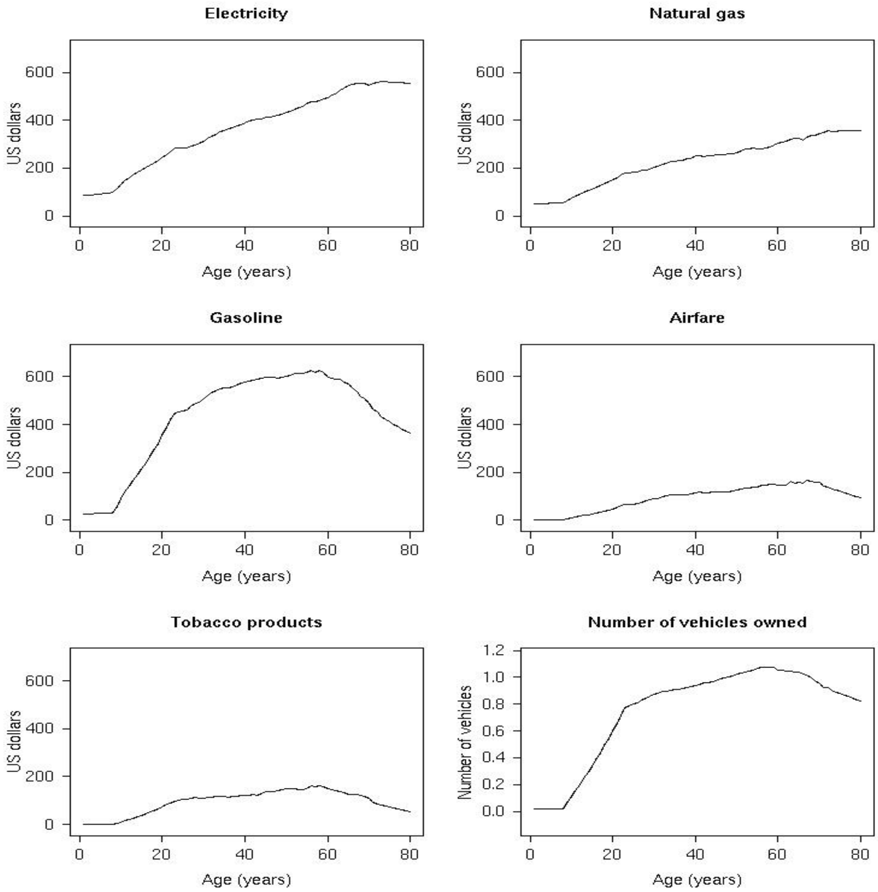
Figure 2: **U.S. profile of age-specific demand for consumption of a selected group of energy-intensive goods, net of the income effect. Estimates are based on the approach suggested by Mankiw and Weil (1989) applied to fractions of household expenditures.**



Data source: Consumer Expenditure Survey 2003.

Figure 3 shows age-specific estimates of consumption obtained using the equivalence scale approach that I suggest. These estimated profiles are qualitatively consistent with the ones obtained using the Mankiw and Weil (1989) approach. The idea behind the equivalence scale approach is to take into account economies of scale and to allocate the observed household expenditure on consumption goods to the members of the household, according to their age.

Figure 3: **U.S. annual average expenditure by age for a selected group of energy-intensive goods. Estimates are obtained using the equivalence scale approach.**



Data source: Consumer Expenditure Survey 2003.

Table 1: **Average expenditure on selected energy-intensive consumption goods for adults living alone, S_a, and for elderly living alone, S_e, in the U.S.**

Consumption good	S_a	S_e
Electricity	482 $	711 $
Natural Gas	355 $	527 $
Gasoline	503 $	342 $
Airfare	122 $	153 $
Tobacco products	156 $	92 $
Number of vehicles owned	0.96	0.77

Data source: Consumer Expenditure Survey 2003.

Table 1 gives the estimated average consumption of the selected goods for adults living alone, S_a, and for elderly living alone, S_e. Table 2 gives the least-squares estimates for the parameters of the equivalence scales for the selected consumption goods, together with the 95% bootstrap confidence intervals (Efron and Tibshirani 1993; Huet, Bouvier, Poursat and Jolivet 2003; Seber and Wild 1989). According to our estimates, economies of scale are noticeable for almost all the selected consumption goods. The extent of economies of scale is largest for the number of vehicles owned, whereas we do not observe any significant economies of scale in consumption of gasoline. The presence of children in households does not have a sizeable impact on consumption of gasoline, vehicles, air flights and tobacco products; it has a noticeable impact on electricity and natural gas consumption.

Table 2: **Estimates of the parameters of the equivalence scale for a selected group of energy-intensive consumption goods.**

Consumption good	Equivalence scale parameters	
	$\hat{\gamma}$	$\hat{\theta}$
Electricity	0.27	0.952
	$(0.208; 0.325)$	$(0.948; 0.955)$
Natural Gas	0.249	0.924
	$(0.146; 0.341)$	$(0.917; 0.93)$
Gasoline	0.054	1.004
	$(0.013; 0.092)$	$(1.001; 1.008)$
Airfare	0	0.948
	$(-)$	$(0.935; 0.963)$
Tobacco products	0	0.941
	$(-)$	$(0.933; 0.953)$
Number of vehicles owned	0.022	0.85
	$(0; 0.045)$	$(0.83; 0.87)$

Note: Numbers in parentheses give the bootstrap 95% confidence intervals.

Data source: Consumer Expenditure Survey 2003.

The leverage of changing mortality levels on carbon dioxide emissions

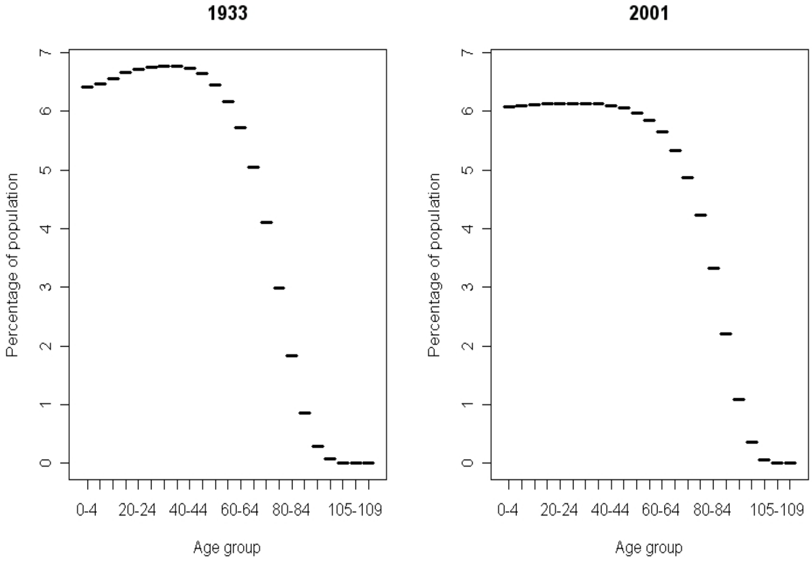
In this section I give some empirical evidence on the role of changing mortality patterns and population aging on energy requirements and carbon dioxide emissions. Following the theoretical framework that I developed in previous sections, I would like to separate the effect of fertility and mortality on age structure and growth rate of a population. I will isolate the effect of mortality on carbon dioxide emissions by doing some exercises of comparative statics and by assuming that the population is in a stable state. I will also look at projections of the U.S population for 2050 to assess the relative importance of population aging and population growth on future emissions.

To get insights on the effect of mortality only, I consider two populations with the same age-specific fertility rates, but different age-specific mortality rates, and I assume that they are in a stable state. By constructing the Leslie matrices for the two populations and by projecting the two populations over a long period of time we obtain the stable age structure associated to the two sets of vital rates. We can thus evaluate how the stable age distribution would change when mortality levels change. For instance, we may want to know how the stable age distribution for the U.S. would change if the current levels of mortality were the ones of the 1930s.

We consider the U.S. population in 2001 and in 1933: we use the female life tables provided by the Human Mortality Database and the fertility rates provided by the U.S. Census Bureau to construct a Leslie matrix based on the vital rates of 2001 and a Leslie matrix based on fertility rates of 2001 and mortality rates of 1933. The two Leslie matrices lead to the stable age structures shown in figure 4: the two profiles show the impact of an increase in life expectancy at birth of 16.7 years, from a starting value of 63.02 years to a value of 79.68, given the U.S. age-specific fertility rates of 2001.

Figure 4 shows the net effect of improving mortality on the age structure, independently of its growth rate effect. Given our estimates of consumption profiles based on the equivalence scale, we can do some exercises of comparative statics: the change in the age structure is associated to a modest reduction of consumption of gasoline (-0.7%) and tobacco products (-2%). On the other hand, this reduction in consumption would be more than counteracted by the increase in consumption of other energy-intensive goods. Consumption of electricity and gas would increase by about 4% and spending in air flights would increase by about 1%. On vehicles owned, we could expect an increase in the order of 1%. These changes are related only to the age distribution of a population and not to its size.

Figure 4: **Stable age structures resulting from the projection over the long run of populations with the fertility rates of U.S. in 2001, and the mortality rates of the U.S. respectively in 1933 and 2001.**



Data source: Human Mortality Database and U.S. Census Bureau.

If we consider the population of the United States in 2007 and its forecast for 2050 according to the U.S. Census Bureau, we can repeat the comparative statics exercise on these figures to get an idea of the effects of changing age structure and size over the next decades, all other factors held constant. In this case, both the change in the age structure and the change in population size put pressure on energy requirements, with the changing population size driving the trend. The overall consumption of electricity and natural gas would increase by about 44%; the consumption of gasoline would increase by about 35% and that of air flights by 39%. Consumption of tobacco products would increase by about 33%. Now, if we look at changes in consumption that are related only to different age distributions over the same period, holding the population size constant, then from the comparative statics exercise we observe an increase in consumption of natural gas and electricity of about 4%. Air flight consumption would increase by 1%. Gasoline and tobacco products consumption would decrease by, respectively, about 2% and 4%.

Changes in consumption of one specific good leads to changes in levels of production in several sectors, according to our input-output economic model. We thus want to explore the consequences of changing levels of consumption of certain goods on the overall energy requirements and carbon dioxide emissions of a country. To account for inter-sectoral flows, we use the economic input-output life cycle assessment(EIO-LCA) model (2008) discussed in Hendrickson et al. (2006), and developed at Carnegie Mellon University.

If we consider electricity, for instance, we observe that an increase in consumption would affect, by order of importance, the power generation and supply sector, oil and gas extraction, stone mining and quarrying, rail transportation, etc. An increase of about 4% in electricity consumption would result, for a country like the US, in an additional consumption of 4523 millions of dollars, which means an increase of emissions of carbon dioxide of 45.3 million metric tons. The same percentage change of natural gas consumption would result in additional consumption of 2983 millions of dollars, implying additional emissions of carbon dioxide of about 4.2 million metric tons only for extraction and distribution of natural gas. The 1% increase in air flights expenditures (or 512 millions of dollars) would translate into an extra 0.86 million metric tons of carbon dioxide emissions. On the other hand, the changing age distribution would entail a reduction of gasoline consumption by 1% (or 919 millions of dollars): this would involve a reduction of carbon dioxide emissions of 0.53 million metric tons from oil extraction and distribution.

The comparative statics exercise gives us a general idea of the importance of a demographic factor such as the age distribution in the explanation of energy requirements and carbon dioxide emissions of an economy such as the one of the United States. The impact of changing age distribution is not extremely large in relative terms, if we consider that in the United States the estimated annual carbon dioxide emissions are in the order of 6000 million metric tons and that large gains in terms of life expectancy may occur throughout a rather long period of time. However, the impact of changing age distribution is relevant in absolute terms, since its magnitude would be in the order of annual emissions of a country such as Ireland.

The combined effect of changing age distribution and population growth, for a forecasted period of about 40 years, is much larger, about ten times bigger than the effect of age distribution by itself.

CONCLUSION AND DISCUSSION

This work is an attempt to discuss the role of demographic dynamics on carbon dioxide emissions, within the theoretical framework of input-output models and stable population theory. In particular, this work originates from the desire of analyzing the complex consequences of population dynamics when relationships between sectors of an economy are taken into account.

I first discussed the role of some demographic dynamics from a theoretical viewpoint; then I applied my reasoning to real data. One important message that emerges from this study is that demographic dynamics have a relevant impact on energy requirements and greenhouse gases emissions. The demographic leverage on emissions can be decomposed into several sources: for instance, changing fertility and mortality levels have a growth rate effect and an age structure effect. The impact of these effects on environmental burdens is not always obvious. For example, improvements in mortality can increase the consumption of gasoline through the growth rate effect; at the same time, the age structure effect tends to reduce gasoline consumption.

In the paper, I started by discussing a stylized model, the stable population theory, and I tried to look at 'limiting' age distributions. I then looked at population projections for the U.S. from the U.S. Census Bureau and I discussed the level of emissions that may be related to future population size and age structure of the U.S.. The empirical analysis shows that changing population age structure may have a noticeable impact on carbon dioxide emissions in the coming decades. However, I estimate that the combined growth rate and age structure effects may be ten times larger than the age structure effect only, for the U.S. in the next four decades.

The focus on past and future demographic history of the U.S. is particularly interesting for two main reasons: first, the U.S. is currently the country with the largest amount of carbon dioxide emissions. Second, in the near future, countries such as China and India may follow demographic and economic trajectories similar to the ones experienced by the U.S., and at a larger scale and faster pace.

From the methodological point of view, I propose a new approach to look at the relationships between demographic and economic dynamics and their leverage on carbon dioxide emissions. The model that I suggest generalizes simpler approaches based on the IPAT equation.

I foresee further research to be pursued to better understand the dynamic relationships between demographic, economic and technological factors.

From the point of view of economic modeling, the results that I present are based on exercises of comparative statics and do not give us information about processes. This is related to the fact that the input-output model is a static representation of the economy and that we hold the per-capita consumption profile by age constant when we consider populations of different sizes and age distributions.

There is some interesting literature in the field of economic demography that looks at relationships between economy and demography in golden rule steady states, under several different assumptions (e.g., Cutler, Poterba, Sheiner and Summers 1990; Diamond 1965; Lee 1994; Willis

1988). Population aging may generate lower aggregate saving rates, but, at the same time, may cause increased capital per worker and higher consumption (Cutler et al. 1990): this fact would mean higher levels of emissions. Lee (1994) shows that population aging may increase or decrease levels of life cycle consumption across golden rule steady states, depending on whether transfers to children or to elderly dominate. Dalton, O'Neill, Prskawetz, Jiang and Pitkin (2008) show that an energy-economic growth model with multiple dynasties of heterogeneous households implies that population aging may noticeably reduce long term emissions.

The dynamic impact of population aging on consumption profiles and thus carbon emissions is still not clear and strongly dependent on the model choice and the underlying assumptions. I based my study on the neutral assumption that the estimated cross-section profile of consumption by age is constant over time. I expect further research to be be done to understand the importance of cohort effects and to improve our understanding of the dynamic relationships between demography, economy and societal rules to better inform the theoretical framework with more realistic assumptions.

From the point of view of modeling demographic dynamics, in this paper I formally considered the role of fertility and mortality patterns. Other important demographic factors such as migration and household dynamics may have a relevant impact on carbon dioxide emissions (Mackellar et al. 1995; O'Neill 2001; O'Neill and Chen, 2002). The explicit incorporation of these factors into our theoretical model, together with the corresponding empirical analysis, may be valuable for the study of contexts with high levels of migration or rapid changes in household structures.

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