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ANALYSIS

Modeling population dynamics and economic growth as competing species: An application to CO_2 global emissions

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ABSTRACT

Since the beginning of the last century the world is experiencing an important demographic transition, which will probably impact on economic growth. Many demographers and social scientists are trying to understand the key drivers of such transition as well as its profound implications. A correct understanding will help to predict other important trends of the world primary energy demand and the carbon emission to the atmosphere, which may be leading to an important climate change. This paper proposes a set of coupled differential equations to describe the changes of population, gross domestic product, primary energy consumption and carbon emissions, modeled as competing species as in Lotka–Volterra prey–predator relations. The predator–prey model is well known in the biological, ecological and environmental literature and has also been applied successfully in other fields. This model proposes a new and simple conceptual explanation of the interactions and feedbacks among the principal driving forces leading to the present transition. The estimated results for the temporal evolution of world population, gross domestic product, primary energy consumption and carbon emissions are calculated from year 1850 to year 2150. The calculated scenarios are in good agreement with common world data and projections for the next 100 years.

1. Introduction

Since the last century, the world has experienced important changes in demographic parameters. Better health care and social improvements have decreased infant mortality and have expanded longevity. As a consequence, world population had increased constantly since 1800 up to approximate 1970, but more recently that annual growth rate has been declining at a high pace, showing a visible demographic transition. This transition presents several aspects, on one side population growth is slowing, but also age structure of the population is changing (the proportion of young people is decreasing and the fraction of elderly people is rising). Moreover, in developed countries, increasing longevity and migration has masked an important reduction trend in fertility. Different countries and regions show different stages of this demographic transition.

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Many developing countries in East and Southeast Asia and Central and Eastern Europe will experience significant aging from about 2020. In other developing countries, however, the demographic transition is less advanced, and working-age populations will increase in the coming decades (IMF, 2004). The question on how to model the population changes has motivated demographers and social scientists to find suitable models and new ideas. This demographic transition will most probably have a real impact on economic growth, and therefore, the development of sound models will be increasingly relevant. Moreover, these changes will also impact on energy primary consumption and carbon emissions, a very sensitive aspect in dealing with global climatic change.

Economic growth has been a major concern among economic theorists for centuries. Despite the different views, population growth has always played an important role. But, while some view population as detrimental to economic growth, others see population as a major contributor.[3] The first type of ideas goes back to the writings of Thomas Malthus (Malthus, 1798). The reasoning was that since land is limited and has diminishing marginal returns to its use, as population increases and the land is harvested more intensely, the economy reaches a zero growth in per-capita GDP. Similarly, though moving away from fixed land to the possibility of reproducible capital goods, Robert Solow (Solow, 1956) came to the conclusion that increasing population produces a slowing economy, since more investment is needed to maintain the same per-capita output. This happens because, when the ratio of machines per worker increases, per-capita output increases as well, each time by diminishing incremental amounts. Hence, at some point, the growth rate of GDP per capita ends up falling to zero. The "solution" to this trap, brought about by the neoclassical economic growth literature, was to assume that the economy grew through an exogenous technical progress (see, for example, the Cass–Koopmans–Ramsey model, from Ramsey, 1928; Cass, 1965; Koopmans, 1965). The role of technological changes in population and economic growth has also been highlighted in several studies (Schumpeter, 1934; Kremer, 1993; Kozulj, 2003).

But it should also be considered that population growth has two effects: It increases the number of consumers and at the same time increases the number of workers devoted to productive activity and research, as well as the scale of the economy. Hence, the so-called "endogenous growth models" (lead by Paul Romer and Robert Lucas in the early 80s) were able to forecast growth of GDP based, not on exogenous technical progress, but rather on the existence of investment on research and development or human capital accumulation that generate by themselves growth (Romer, 1986; Lucas, 1988; and a review of their research in Romer, 1994).[4] Hence, a larger population means more chance of having that kind of effect.

The economic theory debate on whether population growth is detrimental or beneficial to the welfare of humanity essentially comes down to the opposing conclusions of the exogenous versus the endogenous growth models, or in another words, diminishing returns versus creation of technology to overcome them. Empirically, the definition of economic growth as an increase in output per capita implies an inverse relationship between output (GDP) and population, but not necessarily as a cause–effect relationship. If population causes total economical output to increase faster than population does, then it will produce an increase in per-capita output. In fact, data evidence does not unambiguously support either view of population growth. In any of the discussed approaches, it is clear that there is a strong interaction between population and economic output.

In this paper, the population dynamics and economic growth are treated as a dynamic system described by a set of ordinary differential equations in a general form of competing species. The typical predator–prey model or Lotka–Volterra relation (Lotka, 1925 and Volterra, 1926), is well known in the biological, ecological and environmental literature (Carpenter et al., 1994; Janssen et al., 1997; Jost and Arditi, 2000; Jost and Ellner, 2000; Shertzer et al., 2002; Beisner et al., 2003; Song and Xiang, 2006, and many others). These relations have even been applied in other fields, for example, in atmospheric chemistry (Wang et al., 2002), in urban growth studies (Capello and Faggian, 2002; Dendrinos and Mullally 1981, 1983; Puliafito, 2002, 2004, 2007), in the tourist industry (e.g. Casagrandi and Rinaldi, 2002; Hernández and León, 2007). Economic models based on prey–predator relations and system dynamics are used to study the complex feedbacks between economy, population, labor and capital (Goodwin, 1969; Samuelson, 1971; Woodwell, 1998; Johansen and Sornette, 2001; Ramos-Jiliberto, 2005; Krutilla and Reveuny, 2006; Forrester, 1961, 1971).

In parallel to the above discussion of the links between population, GDP and technological change, there is an equally large literature on what are the determinants of world emissions. The environmental economics literature on this issue has two distinct lines of research. A theoretical one, including pollution in mathematical growth models and an empirical one, based mostly on different equations specifications relating mainly carbon emissions to GDP per capita.[5] The theoretical works analyze the difference between optimum and equilibrium and the possible solutions to that gap (standards, taxes, etc.), including modeling of several countries, but with few data counterpart. On the other side, the emission-growth debate in the empirical articles is usually referred to as Environmental Kuznets Curve (EKC), since it reflects that there is an inverted-U relationship between emissions and GDP per capita.[6] The intuition of that shape is that at low levels of growth, the impact on the environment is limited. Then, as development takes-off, resource depletion and waste generation accelerates, while at higher levels of income, increased demand for environmental quality results

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[3] For a detailed review of the literature of the determinants of economic growth, see Barro and Sala-I-Martin (1998).

[4] See Galor and Moav (2006) for a discussion on the importance of human capital in sustaining physical capital accumulation as an explanation for a more collaborative relationship among capitalists and workers. In particular, the authors justify on those grounds why capitalists find incentives to fund education projects.

[5] For a review of the literature on economic growth and the environment, see Panatoyou (2000).

[6] In fact, Kuznets' (1965) original work estimates the linkages between income and inequality.