# A Model of Environment, Economy and Population – an Overlapping Generations Approach*

Ashish Tyagi[a]

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**Abstract**

The Model of Environment, Economy and Population presented here is an attempt to incorporate population dynamics in the literature on climate change. It is a modeling framework for studying the intergenerational and intragenerational welfare implications of climate change mitigation policies and uses a fairly simple OLG approach, instead of an infinitely lived agent approach. It contributes to Population-Environment (P-E) modeling through endogenous demography. The general equilibrium nature of the model makes it easier to introduce perturbation in a sector and analyze its impact in rest of the economy. This approach allows modeling the dispersal of cause and agency and institutional inadequacies associated with the mitigation of climate change. In this way, the framework can be used to indicate policies which are more suited to real-world OLG economies.

*Keywords: Climate Change; Overlapping Generations; Population-Environment (P-E) modeling*

## 1. Introduction

Humans have always lived within the bounds of natural environment, molding it around them to flourish as a species. But there has never been a greater anthropogenic impact on the earth systems as in the present age. Geologically, we might be living in the Anthropocene epoch, which is, as yet, an informal name given to the period during which

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[a] PhD Candidate, Agricultural, Environmental and Regional Economics, Population Research Institute, Pennsylvania State University.
e-mail: ashish.tyagi@psu.edu

human activities have exerted a significant influence on climate and the environment (Crutzen, 2006; Steffen, Crutzen, & McNeill, 2007). This influence has left its distinct mark in the form of global stratigraphic signatures signaling sedimentary, biotic and geochemical changes distinct from the Holocene epoch (Zalasiewicz et al., 2008).

Examining atmospheric carbon dioxide ($CO_2$) concentration levels, Steffen et al. (2007) highlight that starting from a level of around 280 ppm at the beginning of the 19th century, $CO_2$ concentrations increased to around 331 ppm by 1975 and more worryingly, have increased by a similar magnitude in just a brief 3 decade period between 1975 and 2005 to reach 379 ppm. Concentration levels increase continued unabatedly over the last decade and now stands at 398 ppm in the year 2014 (NOAA, 2015) .These levels are the highest ever in the last 0.8 million years (IPCC, 2013).

According to estimates of McNeill (2000), during the period 1890s to 1990s, world population increased by 4 times, industrial output by 40 times and with it, energy use by 16 times. This manifested in carbon dioxide emissions increase of 17 times, with an increase of 13 and 8 times in the emissions of sulfur dioxide and lead, respectively. Perhaps it would better illustrate the point if we elucidate the magnitude of human population increase over the last one and a half century. While the world population did not touch one billion mark till 1804, it has been adding a billion people in shorter and shorter times ever since. The last 4 billion people were just added in the last half century, with the last billion added in just 12 years (UN, 1999, 2012)

The impacts of human activities are clearly visible on the land. Activities like agriculture, deforestation, construction, dam construction etc. have resulted in a significant erosion and anthropogenic denudation of continents, which has left natural sediment production far behind. It is estimated that as geologic agents, humans became the prime agents of erosion sometime during the latter part of the first millennium A.D. (Wilkinson, 2005). Moreover, while anthropogenic soil erosion has led to a significant increase in total soil erosion, less and less of that sediment reaches the world coasts due to retention within reservoirs (Syvitski, Vörösmarty, Kettner, & Green, 2005). To put the extent of mankind's role as geologic agents in perspective, Hooke (2000) estimated that the total volume of earth moved in the past 5000 years by humans will be enough to build a 13,000 ft. high mountain range 25 miles in width and 62 miles in length. Moreover, if the current trend continues then we can build another such mountain range, but this time it will just take 100 years.

Changes made to the terrestrial and marine biosphere by humans are a major cause of biodiversity loss from habitat destruction (MEA, 2005). Moreover, overexploitation of fisheries, spread of alien invasive species through biotic exchange and nutrient loading through the use of synthetic fertilizers and pesticides also result in biodiversity loss. It is estimated that over the past few hundred years, human intervention has resulted in species extinction rates increasing by as much as 1000 times the background rates which were typical over the history of the Earth (MEA, 2005)

This increasing concentration of anthropogenic greenhouse gases manifests in the form of global warming, which threatens the fine natural balance (IPCC, 2013). It is projected that by the end of this century, global surface temperatures are likely to exceed the 1850-1900 levels by at least 2° C if emissions are not reduced as soon as possible (IPCC, 2013). Although the global average surface temperature increase of 2° C appears to be small, it is likely to result in catastrophic consequences through "slow" feedbacks (Hansen et al., 2013).

These “slow” feedbacks give climate change an intergenerational nature. Climate change processes are very slow to take place in nature when compared to an average human lifespan. With the mean lifetime of fossil fuel carbon dioxide emission in the atmosphere being around 30-35 thousand years, it is expected that 17-33% of the fossil fuel carbon will still be present in the atmosphere a thousand years from now (Archer et al., 2009). Therefore, climate change is a long-lasting, resilient phenomenon in the absence of technologies to remove large amount of greenhouse gases from the upper atmosphere quickly and cheaply.

According to Gardiner (2011), climate change problem has three important characteristics. Firstly, there is a dispersion of cause and agency. The longer time scale implies that climate change impacts are seriously back loaded. It is widely agreed that by now we have already committed to a 2° C temperature increases by the year 2100, but the impacts that we feel presently are not the result of present emissions but the emissions generated by humanity in the recent past. This makes the climate change a substantially deferred phenomenon and obscures the connection between cause and effects, undermining the motivation to act. This also creates a disconnection between the benefit and its cost because while present emissions bring most of the benefits to the present generation, the cost will be incurred by the future generations.

Secondly, there is fragmentation of agency. The time dispersion of the problem also exposes the institutional inadequacy of climate change policies. The way democratic political institutions works implies that any mitigation policy arguing for a cost on current generation can easily get out of favor with the voters. The short term political horizon of political institutions is simply too small for a problem working with a century long time scale, raising questions like are current institutions even equipped to deal with the climate change problem?

Finally, a strong assumption is made that countries adequately represent the interests of not only present, but also future generations. But this might not be true. With most of the benefits of emissions skewed towards present generations, there is a serious incentive asymmetry to be biased towards current generations. Therefore, studies assessing climate change impacts, policies for mitigation and adaptation must recognize its intergenerational aspect.

The literature on interaction between economy and the environment employs mathematical models to study the action of economic agents and its long-term impact on environment and growth. Any policy or intervention in the economy then requires an indicator to evaluate its benefits compared to other policies. Calculating total utility under each policy seems to be a reasonably good indicator. But since agents are short-lived and impacts are long-lasting, this indicator needs to sum the utilities across multiple generations. While this aggregation can be modeled in many different ways, current literature generally employs Infinitely Lived Agents (ILA) approach (also called Ramsey approach, or Ramsey-Cass-Koopmans model) to model these environment-economy interactions.

In a Ramsey model, there exist a representative immortal agent whose welfare at any given point in time represents the welfare of the entire generation living in that period. Maximizing the discounted intertemporal utility function for the infinitely lived agent then maximizes the welfare across all generations and yields the consumption paths (Acemoglu, 2009, Chapter 8). Ramsey models have been used in the literature on optimal use of resources (Arrow, Dasgupta, & Mäler, 2003). The empirical literature on environment-economy interaction almost exclusively uses infinitely lived agents approach to assess long-run environmental impact of GHG emissions and efficacy of mitigation policies (Nordhaus & Boyer, 2003; Nordhaus, 1994; Tol, 1997).

But the Ramsey approach has some important shortcomings. Firstly, it undermines the intergenerational aspect of the economy-environment interaction (Azar & Sterner, 1996; Howarth & Norgaard, 1993; Schneider, Traeger, & Winkler, 2008). Faced with high emissions in a particular period, an infinitely lived agent can easily transfer consumption from one moment in time to the other in order to achieve lower emissions but in real world, this is problematic (Beckerman & Hepburn, 2007). As has been discussed already, the institutional inadequacy for emissions control and skewed benefits towards current generations makes it difficult for any such intergenerational transfer to take place in the real world and policy outcomes may be sub-optimal (Ansuategi & Escapa, 2002).

Secondly, although the impacts of climate change during the lifetime of a single generation are small, they are nevertheless important. Since each generation is represented by each point in time for the representative agent in the Ramsey approach, studying intragenerational aspects of mitigation policies is simply not feasible.

Another limitation of the literature on environment-economy interaction is that it ignores the demography of the economy under study and takes the population growth as exogenous. But demographic variables play an important role in the economy by determining the size of the labor force and the dependent population. Economic variables, in turn, influence the demography as highlighted by the Easterlin model, which examines the impact of economic variables on fertility (Easterlin & Crimmins, 1985) and the Preston curve, which highlights the relationship between income levels and mortality (Preston, 1975).

Moreover, recent research has documented the impact of population on environment through the *IPAT* identity, where the environmental impact (*I*) is a function of population (*P*), affluence (*A*) and technology (*T*) (Dietz & Rosa, 1994; York, Rosa, & Dietz, 2003). There have been a few attempts to incorporate this relationship in the literature on climate change (Gerlagh & van der Zwaan, 2001; Lutz, Scherbov, & Prskawetz, 2002) but none has addressed the need to link environment, economy and demography through endogenous population growth.

The main objective of this paper is to develop a modeling framework for studying the intergenerational and intragenerational welfare implications of climate change mitigation policies by using an alternative approach of overlapping generations (OLG) model. In this class of models, multiple generations co-exist in a single time period and economic decision making is relegated to each agent at each time period, who maximize only their own intertemporal utility over their short lifetime. The actions of each generation influences not only their own intertemporal welfare, but also the welfare of future generations through series of interconnected agents. This approach allows modeling the dispersal of cause and agency and institutional inadequacies associated with the mitigation of climate change. In this way, the framework can be used to indicate policies which are more suited to real-world OLG economies.

This paper is a step towards Population-Environment (P-E) modeling, which Lutz, Prskawetz, & Sanderson (2002) argue to be a separate field of analysis. According to Lutz et al., (2002), a P-E model should have four clearly developed features: (i) a population module, (ii) an environment module, (iii) population's impact on environment, and (iv) environment's impact on population. The framework developed here keeps these four points in mind and seeks to fill this gap in the literature. An economic model is added which interacts with population and environment. The resulting Model of Environment, Economy and Population (MEEP) paves the way for policy analysis as it can be applied to real-world data and can be solved through application of computable general equilibrium (CGE) methods.

The model features three generations and two economic sectors, with demographic variables as a function of per capita consumption of the agents from each sector. Economic activity generates emissions which negatively influence productivity in the future, creating intergenerational spillovers. Mitigation policy is in the form of an emission tax on output seeks to shift production away from polluting commodity. The way tax revenues are disbursed among different age-groups (or invested in a trust fund) will have important implication on intragenerational welfare. In addition, the magnitude and timing of taxation will have important intergenerational welfare consequences.

The next section reviews the current literature on the topic. The model framework is presented in section 3.

## 2. Literature Review

There are some challenges that need to be recognized for this research. Firstly, within the OLG model literature, there are various specifications which are possible. The chosen specification needs to be flexible enough to allow for modeling two-way interactions between population, environment and economy. Quite importantly, it should allow for endogenous population growth. Secondly, modeling of emissions in the environment and its impact in the future is a specialized field in itself, but for this research, it needs to be simple enough to highlight major forces at work. Finally, the emission tax policy and the government sector needs to be modeled so that it aids real world policy making, but it has to be kept simple enough to be tractable.

This literature review keeps these challenges in mind and seeks to find solutions to guide the modeling process. Let us start with discussion of the dynastic models and some important considerations for the overlapping generations model.

### *ILA Models and its inadequacies*

In a Ramsey model, the objective of an infinitely lived representative agent is to maximize the discounted sum of all future flow of utility (Barro & Sala-i-Martin, 2004, p. 87)

$$U = \int_0^\infty e^{-(\rho-n)t}\, u[c(t)]\mathrm{d}t$$

where $c(t)$ is the per capita consumption at each point in time, $u(c)$ relates the flow of utility in each period to quantity of consumption, $n$ is the exogenous and constant population growth rate and $\rho$ is the rate of time preference. $u(c)$ is assumed to be increasing in $c$ with diminishing marginal utility, i.e., $u'(c) > 0$ and $u''(c) < 0$. A positive rate of time preference, $\rho > 0$, implies that early consumption is valued more than deferred consumption.

The objective function is maximized through dynamic optimization given the resource constraints and transversality conditions. The basic equilibrium condition highlights the consumption rule

$$r = \rho - \left(\frac{du'/dt}{u'}\right) = \rho - \left[\frac{u''(c).\,c}{u'(c)}\right]\left(\frac{\dot{c}}{c}\right)$$

which states that at the optimal growth path, the rate of return on capital, $r$, equals the rate of time preference, $\rho$, plus the rate of decrease of the marginal utility of consumption, $u'$, due to growing per capita consumption, $c$.

In this model, if emissions in an early time period reduces consumption for future generations and reduce overall utility, then intergenerational transfers from early generations to the far future generations can be theoretically undertaken to return to an optimal growth path. But as discussed before, intergenerational transfers are quite difficult to achieve in the real world.

Moreover, the real-world economy might deviate away from the optimal growth path due to intergenerational spillovers. In their applied experiment of a climate game with deferred rewards, Jacquet et al. (2013) found that when gains from mitigation are spread over several generations, there is very little cooperation to increase those gains. The tendency to cooperate is higher if gains are spread across the lifetime of a single generation, but still lower than cooperation under immediate rewards. This highlights the importance of recognizing intergenerational and intragenerational aspect of the climate change mitigation policy. In the same vein, Marini & Scaramozzino (1995) argue that in order to consider the effect of policy on the trade-off between capital accumulation and environmental quality, the modeling framework must allow for consumer heterogeneity and disconnectedness across generations.

Another shortcoming of the Ramsey approach is the missing life-cycle behavior and resulting lack of macroeconomic insights on the economy under study. For the climate change mitigation policy, a mitigation policy will influence the savings behavior of the generation on which the tax is applied, impacting the capital stock and growth path. Since agents in the Ramsey model do not save to provide for consumption in the later period of life, this resulting link between life cycle behavior and its macroeconomic implications is obscured in the Ramsey model. Using an Overlapping generations model can therefore help overcome the shortcomings of the Ramsey approach and better our understanding of the impact of mitigation policies.

***OLG model and theoretical considerations***

Overlapping generations model were first developed to incorporate life-cycle behavior in the studies of economic growth (Allais, 1947; Samuelson, 1958). The subsequent adaptation of Samuelson (1958) by Diamond (1965) brought the OLG model in the neoclassical framework, making the resulting Diamond OLG model a useful alternative against Ramsey model for many applications (Acemoglu, 2009, p. 327). The canonical Diamond OLG model has two generations alive at any point, with the young generation providing labor force and the old generation providing capital for the production of a single commodity. Returns to labor and capital constituted the income for the young and old generation, respectively. Population growth in this model is exogenous, limiting the usefulness of the Diamond model for the research question here which seeks endogenous population growth.

Another OLG specification used extensively in the literature is the Blanchard-Yaari formulation (Blanchard, 1985). In the Diamond OLG model, mortality at the end of old-age period is certain, but this is not the case in real-world, where economic agents face some probability of mortality at any given stage in their life. Building up on the earlier ideas of Yaari (1965) on life insurance in consumer theory, Blanchard-Yaari model seeks to incorporate this possibility of mortality threat in the perpetual youth model. In this model, an individual is potentially infinitely lived but faces an exogenously given small, but positive probability of his/her life ending at any given time. In other words, the probability that agents will reach the next age-group is not certain, but is given by an exogenous survival probability.

Agents then take this survival probability into account while maximizing their expected utility and savings. Rate of interest in the economy needs to take this survival probability into account so that the annuity market is actuarially fair. Since it acknowledges mortality and provides a framework to model it, this model is an important step towards endogenizing demography in the OLG framework.

However, the Blanchard-Yaari model framework has a serious shortcoming, which is that the survival probability is assumed constant over the entire lifetime of an individual. This constant, age-independent survival probability implies that the life expectancy is same for all individuals which in turn implies that all households have the same propensity to consume across all generations and time periods. The model therefore fails to capture savings by young workers to provide for consumption in the old-age. In this way, the model fails to capture the life-cycle aspect of life, which is the essence of the overlapping generations model (Bommier & Lee, 2003; d'Albis & Augeraud-Véron, 2011). Despite its shortcomings, the Blanchard-Yaari model gives useful insights for a model focusing on better integration of demography in overlapping generations framework. As shown in the next section, MEEP combines the mortality framework of Blanchard-Yaari model with the simplistic generational framework of the Diamond OLG model.

***Endogenizing Demography***

While the mortality framework of Blanchard-Yaari model is helpful, the central question of formalizing population-economy interaction still remains. A possible solution to this issue is the use of Demographic Transition Theory (DTT), which links population evolution and economy through relative importance of agriculture and manufacturing in that economy (Coale, 1973; Davis, 1963; Notestein, 1945). According to DTT, the historical evolution of population across different countries can be divided into four stages (Rowland, 2003, p. 18):

i. Stage one – share of agricultural consumption is high compared to manufacturing. High but relatively balanced fertility and mortality is observed, resulting in low and stable population.

ii. Stage two – increasing manufacturing consumption reduces mortality but agricultural consumption remains high, keeping fertility high and resulting in increasing population

iii. Stage three – further increases in manufacturing consumption and declining share of agricultural consumption results in declining fertility.

iv. Stage four – manufacturing consumption is dominant in total consumption now which results in fertility being very low and in balance with low mortality rate, leading to a stable population.

Based on this theory, by modeling the consumption share of agriculture and manufacturing in agent's problem in the overlapping generations framework, it is possible to endogenize demography so that it follows these specific transition rules. Anderies (2003) used this approach in modeling renewable resource use and growth in a model with endogenous population.

But the demographic transition theory is not without its shortcomings. Over its history spanning more than a decade, the theory has seen disagreements over its depiction of European demographic experience, the timing of mortality decline in relation to fertility decline, and quite importantly, the causal factors in determining historical transitions (Kirk, 1996; Mason, 1997). Despite these disagreements on very specific issues, it is widely agreed that the theory provides a satisfactory framework for broad generalization of economic growth and demographic trends. This implies that a two-sector OLG models of consumable commodities can provide a tractable way to endogenize population.

But in the OLG model literature, a two-sector OLG models of consumable commodities are conspicuously rare. Diamond and Blanchard-Yaari model assume a single commodity which is part-consumed and part-invested. Galor (1992) developed a two-sector overlapping generations model, but it features a pure consumption and a pure investment commodity, which is a restrictive assumption for the purposes of this model. In a two-sector model of agriculture and manufacturing, while it is reasonable to assume that agricultural sector is pure consumption, it would be unreasonable to assume that manufacturing is pure investment. A reasonable assumption would be to treat the latter as a 'mixed' commodity, one which can be consumed as well as invested.

There are very few papers studying a two-sector OLG model with one pure consumption and one mixed commodity. Kalra (1996) proposed such a model and examined the existence of cyclical perfect foresight equilibria. Nourry & Venditti (2012) and Riche, Nourry, & Venditti (2012) study this class of models in the context of business cycle fluctuations and lay-down equilibrium and dynamic properties of the model. Their research provides valuable inputs for two-sector OLG modeling and the present paper seeks to extend their framework by endogenizing population and employing it to study climate change mitigation policies.

An alternative way to endogenize population in overlapping generations framework is the Barro-Becker model of fertility choice (Barro & Becker, 1989; Barro & Sala-i-Martin, 2004, Chapter 9). The model seeks to explain the fertility decline associated with economic growth by treating children as economic commodity, which provide utility to altruistic parents, but also have a cost associated with them (direct costs and an opportunity cost of time). Marginal utility of children decreases with an increase their number and the equilibrium fertility rate is given at the point where the marginal utility equals marginal cost. Since economic growth raises the marginal cost by increasing economic costs as well as opportunity cost of time, fertility declines with economic growth. A corollary is that with economic growth, parents prefer quality of children over quantity.

Despite endogenous fertility in the Barro-Becker model, this paper has still opted for the two-sector approach for endogenizing demography for three reasons. Firstly, the model has been criticized for ignoring jointness of fertility demand with sexual pleasure and failing to account for differing weight parents may place on consumption, labor productivity and old-age security utility that children may provide (Robinson, 1997). Secondly, too much focus on fertility relegates economic activity to the background. For a model incorporating environment, what is needed is a well-specified production sector to model emissions and abatement. The model here keeps this in mind and segregates agriculture and manufacturing to study emission and policy implications separately. Finally, since the objective here is not to explain the demographic transition and its causes, it suffices to take the transition as given and focus on its impact on labor power in the presence of environmental change.

In conclusion, the two-sector OLG framework can tractably address the challenge of modeling population-economy interaction and endogenized population. To complete the modeling framework, what is still needed is an environmental framework to model climate change impact, and a policy framework to model mitigation. Applied OLG models in environmental and resource economics literature can guide us in this regard and the next sub-section is devoted to this discussion.

***OLG models in environmental and resource economics – directions for policy***

The literature here can be divided in a few key areas. Looking at the resource economics first, OLG models have been used to study optimal extraction and intergenerational welfare under exhaustible resource constraint (Gerlagh & Keyzer, 2001; Howarth, 1991a, 1991b). Another group of models have tried to extend the intertemporal welfare analysis to an economy with renewable resources (Farmer & Randall, 1997; Krautkraemer & Batina, 1999). Mourmouras (1993) highlight that in a non-altruistic, overlapping generations economy with renewable natural resources, competition may lead to arbitrarily large declines in living standards, violating the sustainability criteria of intergenerational equity. The model is important for the present topic as it uses government policies like taxation of resource use, subsidy to resource investment and government open market operations in resources market, and studies their efficiency in implementing sustainable resource paths.

Another branch of the literature has sought to incorporate environment as a second commodity in the two-commodity framework. John & Pecchenino (1994) study an economy with a consumption good and environmental quality (in the form of a public good) where environmental quality degrades through capital input use. Marini & Scaramozzino (1995) study a model similar to John & Pecchenino (1994) but environmental quality degrades through the level of economic activity as measured by total production, instead of just capital input use. They characterize this trade-off between economic activity and environmental quality, and derive the conditions for optimal fiscal policy. Using a similar framework, Bovenberg & Heijdra (1998) introduce environmental taxes in the model and study the intergenerational impact of various tax rules. These models have been helpful in guiding this research towards a framework of mitigation policy through taxation.

Another category of models, more closely related to the topic of this work, is the one modeling climate change impact on economy in the overlapping generations framework. Howarth (1996) uses a single-sector economy and climate framework similar to Nordhaus (1994) and shows that the latter's representative agent model for climate policy analysis can be represented as a reduced form case of an overlapping generations model. In a similar framework, Howarth (1998) studies the impact of governmental policies of emission taxes and intergenerational transfers on intergeneration welfare. He finds that stringent emission controls and significant intergenerational transfers are necessary to restrict mean global temperature increase under 2° C in the long run.

Building up on the framework of Howarth (1998), Ansuategi & Escapa (2002) seek to explain the absence of an environmental Kuznets curve for GHG emissions (in other words, they seek to explain the persistence of GHG emissions to be high despite high income levels). They conclude that intergenerational spillovers in the form of lagged impact of emissions and a lack of institutional capacity for intergenerational transfer can explain why GHG emissions do not decline after the economy achieves high income levels. Their result highlights that overlapping generations framework can provide a different perspective in studying climate change issues.

The overlapping generations framework of Howarth (1998) has been very useful in the literature, but it is quite inadequate for this research. The main reason is that the model features a single sector, but the endogenized population framework requires two sectors to model agricultural and manufacturing. Moreover, two sector models also allow studying sector specific mitigation policies. This is important because GHG emissions vary in magnitude across different economic sectors. According to IPCC (2007), in the year 2004, agriculture and forestry, along with the land-use changes together contributed around 31% to total emissions, with energy supply contributing around 26% and industrial sector contributing around 20%. Since the contribution of each sector to the national income varies greatly, mitigation policies in agricultural sector can have very different macroeconomic implication compared to mitigation policies in the manufacturing. Therefore, sector specific policies can highlight a richer general equilibrium dynamic as compared to a single commodity model.

Despite this limitation, Howarth (1996, 1998) model is very helpful for this research as it adapts Nordhaus (1994) environmental framework to OLG modeling and has been influential in modeling environment-economy interactions in this research.

Other attempts at overlapping generations modeling have been fairly ambitious with an objective to present an alternative to dynastic Integrated Assessment models (IAM). The Population-Environment-Technology (PET) Model (Dalton & Goulder, 2001) is an IAM that seeks to project global fossil-fuel based $CO_2$ emissions over a long time-horizon of a century or more. The model includes multiple production sectors, global regions and various government policy measures for abatement. Although the population growth is modeled flexibly by incorporating various scenarios from UN estimates, it is still exogenous.

Gerlagh & van der Zwaan (2001) present Applied Long-term Integrated Competitive Equilibrium Model (ALICE) to study the effects of ageing and environmental trust fund on the interest rate, which influences the level of efficient GHG emissions reductions. An important feature of this model is the presence of an environmental trust fund for government policy. Instead of redistributing emission tax revenue back to the alive generations, it is invested in a trust fund to ensure that resource claims of future generations are met.

A similar idea is applied in the framework here, where the government can either redistribute tax revenues back to the young or old generation (with differing impact on emissions) or it can invest all or a part in a trust fund, which can be seen as investment in research and development. It reduces the available manufacturing commodity available to current generation, thereby reducing emissions, and also has a positive impact on future productivity through total factor productivity.

Summing up the important points from this review, firstly, a two-sector overlapping generations model with an agricultural commodity which is fully consumable, and a manufacturing commodity which can be consumed as well as invested, can help endogenize population by linking sector-specific per capita consumption to fertility and mortality through demographic transition theory. Secondly, the environment-economy interactions can be kept simple enough by using the existing framework of Nordhaus (1994) and its adaptation to OLG models by Howarth (1998). Finally, mitigation policy can be modeled through sector-specific emission taxes which take into account sectoral emissions and their macroeconomic impacts. The resulting tax revenue can be redistributed to young generation, the old generation or it can be invested in the trust fund. The magnitude and nature of the fiscal policy will determine the intergenerational and intragenerational welfare implications, study of which is the focus of this research.

Keeping these points in mind, a general form of the model is introduced in the next section.

## 3. The model of environment, economy and population

A basic framework of the model is presented in Figure 1, where rectangular boxes show particular sectors (or agent groups), arrows show flows (dashed arrows representing future flows) and oval boxes highlight intermediating factors. On the left hand side, there is a population of economic agents who provides labor and capital inputs to the production

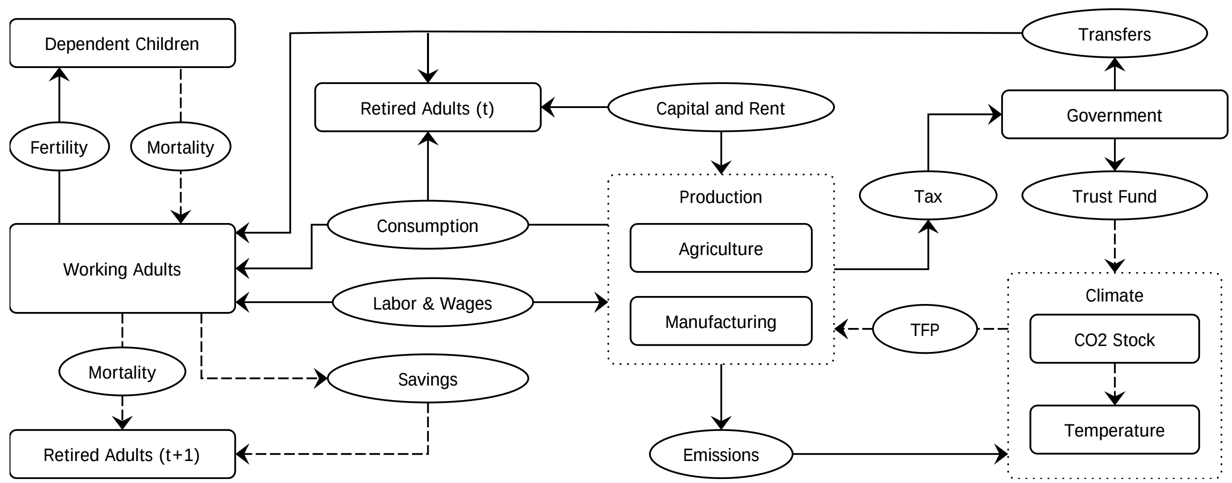


*Figure 1*

sector (in the middle) in return for factor incomes, and also purchase the final output for consumption or investment. In the production sector, agriculture and manufacturing activity creates GHG emissions, which increase the $CO_2$ stock (bottom right side), influencing future temperature, which impacts the productivity in the economy with a time-lag. Government (top right side) can impose a tax on production activities in order to curtail emissions and can use the revenue to make transfers to current generations or future generations through a trust fund which helps mitigating the impact of climate change.

There are three major innovations in this model. First is the application of a two-sector overlapping generations framework (with agriculture as a consumable commodity and manufacturing as a mixed commodity) in the literature on climate change mitigation policies. Second innovation is the framework for endogenizing demography in a model of climate change. The third innovation is the Economy-Environment-Population modeling which not only develops each of the three modules clearly, but also specifies pathways for interactions among them.

Consider an economy with 3 generations; children $(c)$, working adults $(y)$ and retired adults $(o)$, at any given discrete time $t$. There are two sectors in the economy; an agricultural sector producing commodity 1, which is a pure consumption good, and a manufacturing sector producing commodity 2, which can be consumed as well as invested. Both these commodities are produced by a representative firm using 2 inputs; capital and labor.

A representative working adult is endowed with 1 unit of labor power which the agent provides to production sectors inelastically, to earn income which can be spent on own consumption, consumption of children (who are dependent on parent for consumption) and on savings for retirement. Retired adults do not provide any labor services but own all the capital stock in the economy and earn an interest on it, which they spend on consumption.

***Demography***

Denote $x_{it}^{j}$ as per capita consumption of commodity $i \in \{1, 2\}$ for a representative agent belonging to age-group $j \in \{c, y, o\}$ at any given time $t$. Denote $H_t^j$ as total population of age-group $j$ at time $t$ and $H_t = \sum_j H_t^j$ as total population in the economy at time $t$. Demographic change is determined by age-specific fertility rate $\psi_t^j$ and age-specific survival rate $\chi_t^j$ for age-group $j$ at time $t$.

$\psi_t^j$ is the number of children that an individual in age-group $j$ will have at time $t$. It is assumed that children and retired adults have fertility rate of 0. $\chi_t^j$ is the probability that an individual belonging to age-group $j$ at time $t$ will transition to an older age-group at time $t+1$. It is assumed that none of the retired adults survive at the end of each period. Therefore, the demographic variables in vector form can be denoted as

$$\psi_t = \begin{bmatrix} \psi_t^c & \psi_t^y & \psi_t^o \end{bmatrix} = \begin{bmatrix} 0 & \psi_t^y & 0 \end{bmatrix}$$

$$\chi_t = \begin{bmatrix} \chi_t^c & \chi_t^y & \chi_t^o \end{bmatrix} = \begin{bmatrix} \chi_t^c & \chi_t^y & 0 \end{bmatrix}$$

Following the framework of Anderies (2003), it is assumed that age-specific fertility and mortality depends on the relative sectoral consumption of representative agent in each group. These rates are specified so that they follow population evolution as under Demographic Transition Theory as discussed in the previous section.

Define the fertility rate for working adults at time $t$ as

$$\psi_t^y = b_0 \left(1 - e^{-b_1 x_{1t}^y}\right) e^{-b_2 x_{2t}^y}$$

where, $x_{1t}^y$ and $x_{2t}^y$ denote the per capita working adult consumption of agricultural and manufacturing good, respectively, $b_0$ is the maximum number of children an adult can have, and, $b_1$ and $b_2$ denote the responsiveness of fertility to agricultural and manufacturing per capita consumption, respectively. Note that $\partial\psi_t^y / \partial x_{1t}^y \geq 0$, implying that increasing agricultural consumption by working adults increases the fertility rate. Also note that $\partial\psi_t^y / \partial x_{2t}^y \leq 0$ implying that increasing per capita manufacturing consumption of working adults reduces the fertility rate. For any given $b_0, b_1$ and $b_2$, zero per capita manufacturing consumption implies a non-zero fertility rate, but a zero per capita agricultural consumption implies fertility rate of 0, highlighting the necessity of agricultural consumption for the survival of population.

Similarly, define the age-specific survival rates at time $t$ for age-groups $\bar{j} \in \{c, y\}$ as

$$\chi_t^{\bar{j}} = 1 - d_{0\bar{j}} e^{-x_{1t}^{\bar{j}}\left(d_{1\bar{j}} + d_{2\bar{j}} x_{2t}^{\bar{j}}\right)}$$

where the second term on the RHS denote mortality rate. Here $x_{1t}^{\bar{J}}$ and $x_{2t}^{\bar{J}}$ denote per capita consumption of agricultural and manufacturing of a member of age-group $\bar{J}$, respectively, $d_{0\bar{J}}$ is the maximum mortality rate and, $d_{1\bar{J}}$ and $d_{2\bar{J}}$ are the sensitivity of mortality to agricultural and manufacturing consumption respectively. Note here that $\partial\chi_t^{\bar{J}}/\partial x_{1t}^{\bar{J}}$ and $\partial\chi_t^{\bar{J}}/\partial x_{2t}^{\bar{J}}$ are both non-negative, and hence, increasing per-capita consumption for any commodity increases the survival rate for that age-group. Also note that if agricultural per capita consumption is 0, then survival rate is also 0, highlighting the essential nature of agricultural consumption.

The equations of motion for age-specific population are then derived as

$$H_t^c = \psi_t^y \, H_t^y$$

$$H_{t+1}^y = \chi_t^c \, H_t^c$$

$$H_{t+1}^o = \chi_t^y \, H_t^y$$

Let labor supply at time $t$ be denoted as $L_t$, then the equation of motion for labor supply is given as $L_t = (1 + \hat{n}_{t-1})L_{t-1}$, where $\hat{n}_{t-1}$ is the rate of growth of labor force and can be calculated through this equation because $L_{t-1}$ and $L_t$ are known from the demographic module.

***Production***

Production in sector $i \in \{1, 2\}$, where 1 denotes pure consumption agricultural sector and 2 denotes mixed (can be consumed and invested) commodity manufacturing sector, at time $t$, takes place according to the production function

$$X_{it} = F_i(A_{it}, K_{it}, L_{it})$$

where $A_{it}$ is the total factor productivity, $K_{it}$ is capital input and $L_{it}$ is the labor input. $r_t$ denotes the price of capital and $w_t$ is the wage rate. The market price for each commodity is $p_{it}$.

The production function is assumed to be twice continuously differentiable and satisfying the following neoclassical assumptions (Barro & Sala-i-Martin, 2004, sec. 1.2.1):

i. Homogeneity of degree 1 in K and L

ii. Positive and diminishing returns to capital and labor: ${F_i}_{K_i} > 0, {F_i}_{L_i} > 0, {F_i}_{K_iK_i} < 0$ and ${F_i}_{L_iL_i} < 0$, where the subscript $K_i$ or $L_i$ denotes first derivative with respect to the input and subscript $K_iK_i$ or $L_iL_i$ denotes second derivative with respect to the input.

iii. Inada conditions: which state that the marginal product of a non-zero input approaches infinity as the input goes to 0 and approaches 0 as the input goes to infinity.

$$\lim_{K_i \to 0}\left(\frac{\partial F_i}{\partial K_i}\right) = \lim_{L_i \to 0}\left(\frac{\partial F_i}{\partial L_i}\right) = \infty$$

$$\lim_{K_i \to \infty}\left(\frac{\partial F_i}{\partial K_i}\right) = \lim_{L_i \to \infty}\left(\frac{\partial F_i}{\partial L_i}\right) = 0$$

Using the assumption of homogeneity, production functions can be written in the intensive form as

$$X_{it} = F_i(A_{it}, K_{it}, L_{it}) = L_{it} \, . F_i\left(A_{it}, \frac{K_{it}}{L_{it}}, 1\right) = L_{it} f_i(k_{it})$$

where $k_{it} = K_{it}/L_{it}$ is the capital per labor in sector $i$ and $f_i(k_{it})$ is defined as equal to $F_i\left(A_{it}, \frac{K_{it}}{L_{it}}, 1\right)$. Defining $x_{it} = X_{it}/L_t$, we get the production function in the intensive form as

$$x_{it} = l_{it} . f_i(k_{it})$$

where $l_{it}$ is the fraction of labor force employed by sector $i$ at time $t$. Marginal products of the factor input in each sector are then given by

$$\frac{\partial F_i}{\partial K_{it}} = f_i'(k_{it})$$

$$\frac{\partial F_i}{\partial L_i} = f_i(k_{it}) - k_{it} . f_i'(k_{it})$$

The economy is bound by resource constraints

$$L_{1t} + L_{2t} = L_t; \quad K_{1t} + K_{2t} = K_t$$

which can be written in the intensive form as

$$l_{1t} + l_{2t} = 1; \quad l_{1t} k_{1t} + l_{2t} k_{2t} = k_t$$

The equation of motion for capital stock is given by the following equation

$$K_{t+1} = (X_{2t} - Z_{2t}) + (1 - \delta) K_t$$

where $Z_{2t}$ is the aggregate consumption from the mixed manufacturing commodity and $\delta > 0$ is the depreciation rate. Dividing both the sides by available labor in time $t$, we get the equation of motion in per worker terms as

$$\frac{K_{t+1}}{L_t} = (x_{2t} - z_{2t}) + (1 - \delta) k_t$$

where $x_{2t}, z_{2t}$ and $k_t$ denote the per worker quantities. Using $L_{t+1} = (1 + \hat{n}_t)L_t$, the LHS can be written as

$$(1 + \hat{n}_t)k_{t+1} = (x_{2t} - z_{2t}) + (1 - \delta)k_t$$

Production also generates emissions $e_{it}$ through the relationship

$$e_{it} = \sigma_{it} X_{it}$$

where $\sigma_{it} \geq 0$ are fixed emission factors, giving total emissions in the economy as

$$e_t = \sum_i \sigma_{it} X_{it}$$

Government imposes emission taxes $g_{it}$ on emissions generated by each sector. The problem for producers then is to

$$\max_{L_{it}, K_{it}} p_{it} F_i(A_{it}, K_{it}, L_{it}) - w_t L_{it} - r_t K_{it} - g_{it} e_{it}$$

***Consumption***

As mentioned earlier, let $x_{it}^j$ denote the per capita consumption of an agent in age-group $j \in \{c, y, o\}$ and commodity $i \in \{1, 2\}$ at any time $t$. Working adults are responsible for the consumption of children. Agents have age-specific utility function $u_y(x_{1t}^c, x_{2t}^c, x_{1t}^y, x_{2t}^y)$ when they are in the age-group of working adults and utility function $u^o\left(x_{1,t+1}^o, x_{2,t+2}^o\right)$ when old. Lifetime utility function is given by $U\left(u_y(\cdot), u_o(\cdot)\right)$ and it is assumed that $U$ is twice continuously differentiable, increasing in $x_{it}^j$, strictly quasi-concave and satisfies Inada conditions given by

$$\lim_{x_{1t}^j \to 0} \frac{\partial U}{\partial x_{1t}^j} = \lim_{x_{2t}^j \to 0} \frac{\partial U}{\partial x_{2t}^j} = \infty$$

$$\lim_{x_{1t}^j \to \infty} \frac{\partial U}{\partial x_{1t}^j} = \lim_{x_{2t}^j \to \infty} \frac{\partial U}{\partial x_{2t}^j} = 0$$

for each $j \in \{c, y, o\}$. It is also assumed that old-age consumption of both the commodities is a normal good.

Working adults earn an income of $w_t$ from employment in the production sector and a transfer $T_t^y$ from the government. This income is spent on own consumption, consumption of their children and on saving an amount $\varphi_t$ for the old age. The amount $\varphi_t$ is utilized to purchase capital (existing stock and additions from manufacturing commodity at time $t$) denoted by $k_{t+1}^y$ at price $p_t$. This capital is rented to firms in the period $t + 1$, where it earns a rate of return $r_{t+1}$ and at the end of the period, the undepreciated capital stock is sold to young generations at price $p_{2,t+1}$.

In their old-age, agents earn a return $R_{t+1}$ on their savings $\varphi_t$ and receive a transfer $T_{t+1}^o$ from the government. The budget constraints can then be written down as

$$\psi_t^y(p_{1t}x_{1t}^c + p_{2t}x_{2t}^c) + \left(p_{1t}x_{1t}^y + p_{2t}x_{2t}^y\right) + \varphi_t \leq w_t + T_t^y$$

$$p_{1,t+1}x_{1,t+1}^o + p_{2,t+1}x_{2,t+1}^o = R_{t+1}\varphi_t + T_{t+1}^o$$

where, $\psi_t^y$ is the number of children per adult decides to have and is endogenously determined by adding an equation for adult fertility $\psi_t^y = b_0\left(1 - e^{-b_1 x_{1t}^y}\right)e^{-b_2 x_{2t}^y}$, which balances the system of equation. $R_{t+1}$ denotes the return on per worker savings. The problem for working adults at time $t$ then is to

$$Maximize_{\,x_{1t}^c, x_{2t}^c, x_{1t}^y, x_{2t}^y, x_{1t}^o, x_{2t}^o} U\left(u_y(x_{1t}^c, x_{2t}^c, x_{1t}^y, x_{2t}^y), u^o(x_{1t+1}^o, x_{2t+2}^o)\right)$$

subject to the budget constraints

$$q_t^c(p_{1t}x_{1t}^c + p_{2t}x_{2t}^c) + \left(p_{1t}x_{1t}^y + p_{2t}x_{2t}^y\right) + \varphi_t \leq w_t + T_t^y$$

$$p_{1,t+1}x_{1,t+1}^o + p_{2,t+1}x_{2,t+1}^o = R_{t+1}\varphi_t + T_{t+1}^o$$

Working adults spend an amount $\varphi_t$ on purchasing capital stock (manufacturing output), which can be denoted in per worker form here as $k_{t+1}^y$ at price $p_{2t}$.

$$p_{2t}k_{t+1}^y = \varphi_t$$

The total return on savings include a market rate of return $r_{t+1}$, proceeds from the sale of undepreciated capital to younger generation at the end of the period $(1-\delta)p_{2,t+1}$, and a survival factor $\left(\chi_t^y\right)^{-1}$. $\chi_t^y$ is the probability that an individual belonging to working-adult age group at time $t$ will successfully transition to old-age group at time $t+1$. This implies that

$$\frac{r_{t+1}}{\chi_t^y}k_{t+1}^y + (1-\delta)p_{2,t+1}k_{t+1}^y = R_{t+1}\varphi_t = R_{t+1}p_{2t}k_{t+1}^y$$

$$R_{t+1} = \frac{r_{t+1}/\chi_t^y + (1-\delta)p_{2,t+1}}{p_{2t}}$$

which gives the gross rate of return on capital. A survival factor $\left(\chi_t^y\right)^{-1}$ is required to enforce actuarially fair market condition similar to the Blanchard-Yaari model. This can be explained with a simple example. Assume that there are $l$ adult members making a decision to save some amount summing up to $Y$. Assume a survival rate of $0 < \chi_t^y \leq 1$, indicating that only $\chi_t^y$% of the working adults will make it to the next age-group. In the case where the investment bank provides agents a rate of return $r$, the total amount with the bank in next period is $(1+r)Y$, out of which the bank disburses $\chi_t^y(1+r)Y$ and keeps $(1+r)Y - \chi_t^y(1+r)Y = (1-\chi_t^y)(1+r)Y \geq 0$, with it. This is not an actuarially fair market as the bank ends up with a profit. In order for it to be actuarially fair, the bank needs to take the survival rate into the calculations for return.

In an actuarially fair market, the bank offers a rate of $1 + r/\chi_t^y$ with a total amount of $(1 + r)Y$ with it in the next period. It disburses $\chi_t^y(1 + r/\chi_t^y)\, Y = (1 + r)Y$ to the people and is left with $(1 + r)Y - (1 + r)Y = 0$. It is important to note that the market return is still $r$ and the bank appraises the money to $(1 + r)Y$ and not a higher value of $\left(1 + r/\chi_t^y\right) Y$.

***Government***

A balanced budget is assumed where the government seeks to equate tax revenues with total transfers. That is,

$$\sum_i \sigma_{it} g_{it} X_{it} = T_t^y H_t^y + T_t^o H_t^o + cf_t$$

where the LHS is the tax revenue, and the RHS is the sum of transfers and investment in the trust fund $cf_t$ at time t. It can be argued that a budget deficit may increase welfare, but introducing the possibility of a budget deficit will also require introduction of a government bond market. A balanced budget assumption helps to avoid this complication, which can be studied in future extensions.

The equation of motion for trust fund is

$$CF_{t+1} = \left(1 - \delta_{cf}\right) CF_t + cf_t$$

where $\delta_{cf}$ is the depreciation on trust fund investment. This trust fund is used to purchase manufacturing commodity and can be seen as investment in climate change research and adaptation, which not only crowds out investment, but also has positive impact on future productivity.

The government can choose to provide all transfers to young people (who save some part of it and reduce production, and hence emissions), or all to old-age people (who consume all of it), or all in trust fund (where all of it is saved and gives maximum reduction in production). It is also possible to choose a combination of these 3 policies. This policy is the crux of the scenario analysis, which is discussed in the next section.

***Climate***

The climate module is based on Howarth (1998), with an addition of environmental trust fund for mitigation. Temperature is assumed to be increasing in emissions from previous periods and decreasing in the trust fund stock

$$Temp_t = T(e_0, e_1, \dots, e_{t-1}, CF_{t-1})$$

where $CF_{t-1}$ denotes the trust fund stock at time $t - 1$.

TFP depends on three factors; first, an exogenous technological progress factor which positively impacts TFP over time (with the rate decreasing, constant or increasing in different scenarios), second is the negative impact of temperature increase on productivity and third is the negative impact of mitigation on production. A suggestive form can be

$$A_i = \bar{A}_i \times \xi_{1i}(1 - Temp_t) \times \xi_{2i}(e_{it}/e_{i0})$$

In the specification above, as exogenous TFP $\bar{A}_i$ increases, production increases. As $Temp_t$ increases, production declines. As emissions are mitigated by bringing $e_{it}$ to a figure lower than $e_{i0}$ production declines.

***General equilibrium conditions***

Market clearing conditions imply that both the factor markets and both the commodity markets clear. That is, $\forall\, i \in \{1, 2\}$ and $\forall\, j \in \{c, y, o\}$,

$$\sum_i L_{it} = H_t^y; \quad \sum_i K_{it} = K_t$$

$$\sum_j H_t^j x_{1t}^j = X_{1t}; \quad \sum_j H_t^j (x_{2t}^j) + H_t^y \left(\frac{\varphi_t}{p_{2t}}\right) + \frac{cf_t}{p_{2t}} = X_{2t}$$

The last of these equations is quite important as it requires that the total output of manufacturing commodity must equal the sum of the demand arising from consumption by all three age-groups, the demand for investment from working adults and the demand for trust fund investment.

***Scenario Analysis and model application***

In order to examine intergenerational welfare under different emission tax rates and government policies regarding transfers and trust fund, there are four main scenarios of interest:

*Scenario 1:* No emission tax and no transfers (baseline)

*Scenario 2:* Emission taxes and all revenue distributed as transfers (with sub-scenarios focusing on different tax rates, different share of working adults and retired households in transfer disbursal)

*Scenario 3:* Emission taxes and all revenue invested in trust fund (sub-scenarios on different tax rates).

*Scenario 4:* Emission taxes and all revenue shared between transfers and trust funds (with sub-scenarios focusing on different share ratios and different tax rates)

In the work under progress, the framework proposed here is applied to a global data to highlight the inter- and intra-generational welfare implications of a climate change mitigation policy.

## 4. Concluding Remarks

The Model of Environment, Economy and Population presented here is an attempt to incorporate population dynamics in the literature on climate change. It also contributes to the literature by allowing a fairly simple OLG approach, instead of an infinitely lived agent approach, and allows us to compare inter-generational welfare across time. The major innovations are the endogenized demography and the modeling of economy-environment-population interactions. The general equilibrium nature of the model makes it easier to introduce perturbation in a sector and analyze its impact in rest of the economy. In this way, the model shows promises for many extensions.

On the demographic front, much can be learnt from existing OLG models in macroeconomics field and it is possible to incorporate education, human capital and sex ratio (Blackburn & Cipriani, 2002; Galor & Weil, 1993; Greenwood & Seshadri, 2002) in the model. It is also feasible to divide the populations by 5 year age-groups and simulate population life tables to create more realistic models and find better policy predictions.

On population to environment interaction, the impact of demographic changes like ageing, urbanization, changes in household size and their impact on energy intensity of the economy can be incorporated (Dalton, O'Neill, Prskawetz, Jiang, & Pitkin, 2008; Liddle & Lung, 2010; O'Neill et al., 2012). In a multi-region model, it might be interesting to model trade with emissions linked to consumption instead of production so that mitigation policies target the ultimate consumer who demands those emissions (S. J. Davis & Caldeira, 2010; Rothman, 1998).

On environment to population interactions, it is possible to include direct consequences of global warming on health of the future generations (Epstein, 2000; Patz, Campbell-Lendrum, Holloway, & Foley, 2005) and study the impact of global warming on migration and social welfare (Bencivenga et al., 2014; Galor, 1986) in a multi-region framework.

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