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Climate Change Impacts on Economic Growth: A Theoretical and Panel Data Analysis

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Abstract

This paper develops a theoretical model of endogenous growth where both human and physical capitals depreciate due to environmental pollution by extending the framework in Bretschger and Valente (2011). The model allows for adaptation to environmental effects triggered due to climate variation. We characterize the socially optimal path of an economy in which pollution is generated by physical capital accumulation, which affects the depreciation rate of both the types of capital. The harmful effects of pollution might be severe for countries vulnerable to climate change. Solving for the social planner's equilibria, we find that along the optimal path, economic growth is lower when the efficiency loss in physical and human capital stock due to climate change is higher, the pollution intensity of physical capital is higher, the vulnerability of a country to climate change is higher or the adaptation efficiency of the country to climate change is lower. The long-run growth rate of income and consumption is found to be the same as that of physical capital, human capital and pollution growth rate. These results are tested empirically for a balanced panel of 62 countries including both developing and developed countries for a time spanning 1995-2016. We capture the vulnerability of human capital of a country to climate change through environmental health index (EHI) and physical capital vulnerability through CO_2 intensity. The empirical results based on FGLS country fixed effect method show that higher environmental health index (EHI), which is a proxy for higher human health and lower vulnerability of the country human capital to climate change, has a positive impact on the GDP of the country. The higher efficiency loss of investment in physical capital stock due to climate change as measured by CO_2 intensity has significant negative impact on the GDP of the country. Moreover, these negative effects are not symmetric across different sectors of the economy, the negative effects of climate change are more severe for the agriculture sector of the economy.

JEL Classification: C23, J24, O44, Q54.

Keywords: Adaptation capacity, climate change, economic growth, environmental health, panel data analysis, fixed effects model, feasible generalized least square estimation.

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1. Introduction

At the 22nd Conference of Parties meeting of the United Nations Framework Convention on Climate Change (UNFCCC), held in Marrakech, Morocco, from 7-18 November 2016, Parties recognised the need for adaptation to the expected impacts of climate change. The Parties agreed to provision of adequate financial support and international cooperation on climate-safe technologies and capacity building to developing nations to enable them to enhance their adaptation actions to address climate change. This is because it is increasingly felt that the capacity building efforts of developing countries, to the extent that these are not in conflict with their developmental objectives, are necessary for meeting the global climate change mitigation targets. With this, the question arises that is what impact will capacity building efforts will have on the economic growth and welfare of the developing countries.

Given that the pollution in the atmosphere will increase higher the pollution intensity of the production, a deteriorated environment poses severe constraint for sustained economic growth by intensifying health problems and frequent natural disasters caused by global warming. Climate change poses a severe threat to human capital, comprising skills, knowledge and good health, all of which constitute a basic prerequisite toward achieving higher economic growth. Learning capacity is likely to be undermined by climate related disasters. Health risks would impact the individual's ability to contribute to higher economic growth. In addition, global climate change will raise the loads of indoor and outdoor heat that is likely to may harm productivity and health of millions of working people. It is predicted that climate change would reduce labor productivity by 11-27% unless employers invest in adaptive measures (Kjellstrom et. al., 2008). Thus, environmental change and climatic variations would adversely impact human capital stock through negative health effects, which, in turn, would reduce the growth of real GDP (Sapci 2013).

Furthermore, capital stock is also under threat from rising average global temperatures and its associated effects. For example, the floods in Thailand in 2011 caused total damage, amounted to $40 billion, more than 1/10th of the country’s GDP. The typhoon in the Philippines in 2013 led to losses of $12 billion. This implies that a higher risk of natural disaster inhibits the process of capital accumulation, not only by direct destruction of the stock but also by reducing the expected return from investing in new production facilities. If these weather-related disasters are identified, it is clear that at some point further economic growth will become unsustainable.

Given this background, this research attempts to explore the growth implications of climate change. There exists a large body of empirical and theoretical literature on this subject. The studies are either theoretical or empirical in nature. The purpose of the theoretical models is to explore how the levels, paths or growth rates of crucial variables such as investment, output, consumption, and environmental pollution are affected if environmental dimensions are incorporated in the standard economic growth models (see Xepapadeas, (2006)) for an extensive discussion of literature in this regard). Ikefuji and Horii (2012), utilize an endogenous growth model to analyze the risk of physical capital destruction caused by using polluting input in production on the sustainability of economic growth. They find that economic growth is not sustainable in the long run because the risk of natural disasters eventually rises to the point at which agents do not want to invest in capital any further. Pollution has negative health effects, and health is an important part of human capital. Hence, environmental degradation lowers economic growth by lowering human capital investments through negative health effects (Sapci, 2013; Zivin and Neidell, 2012). Several mechanisms have been suggested through which climate change suppresses growth in absolute and per capita terms. Climate change could also lead to lower labor productivity growth (Kemel et. al., 2009) or lower human capital accumulation and, accordingly the rate of technical progress (Frankhauser and Tol, 2004; Lecocq and Shalizi, 2007). Working through changes in temperature, climate change lowers the marginal product of physical and human capital, which in turn leads to a decline in per capita GDP (Choiniere and Horowitz, 2000).

In comparison, the empirical studies mainly discuss and analyze the association between temperature/ climate and economic performance (i.e., per capita income, economic growth) over long periods of time in sample countries. These studies mainly examine the association between temperature/ climate change and economic performance (i.e. per capita income, GDP growth rate and indicators of economic development) (see, for instance, Nordhaus, 2006; Geffersa and Abebayehu, 201; Odusala and Abidoye, 2015; Alagidede, 2014). Higher temperature is found to have large negative effects on economic growth, reducing agricultural output, industrial output, and aggregate investment, but only in poorer countries. In richer countries, changes in temperature are found to have no discernable effect on growth (Dell, 2008). This causal interpretation of the association between temperatures and higher incomes has been strengthened by Dell, Jones, and Olken (DJO, 2009), who find that not only does income per capita falls by 8.5% due to per degree Celsius rise in mean national temperature, but that this negative relationship between temperature and income holds even within countries, and even within regions within countries. Moving beyond simple cross-sectional regressions, Dell, Jones, and Olken (DJO, 2012) investigate the relationship between temperature and standards of living by exploiting fluctuations over time in the weather patterns. As in the case of cross-sectional regressions across countries, their panel data analysis implies that colder temperatures are better: higher temperatures reduce agricultural output and induce political instability, with direct knock-on effects on economic growth.

In general, the main finding of the afore-mentioned studies on the impact of temperature rise on per capita income is that temperature and income move in opposite direction and their correlation is statistically significant. These studies do not emphasize the mechanisms through which climate change lowers economic growth. Although climate change leads to lower economic growth, this relationship is not symmetric across countries. The developing countries are more likely to be hurt because they lack resources necessary for adaptation to climate change (Bretscher and Valente (2011)). These destructive effects can be reduced through investment in productive infrastructure that is susceptible to climate change, or in adaptive assets, which is not intrinsically productive, but mitigate climate damages (Millner and Dietz, 2011). Environmental protection and sustained growth could be achieved only if investment is made in knowledge capital and resources are devoted to efficient methods of pollution prevention (Xepapadeas, 2006). But low-income countries are typically less able to adapt to climate change both because of less capable institutions and lack of resources (Toll, 2009). The negative short-term effects of temperature are generally offset in the long run through adaptation (Dell, 2009).

Unlike earlier studies wherein pollution lowers the economic growth of the country by reducing human or physical capital stock accumulation this paper develops an endogenous growth model in which climate change affects both human and physical capital depreciation. Climate change affects human capital accumulation through negative health effects. It also reduces the physical capital accumulation through pollution induced decline in the efficiency of physical capital investment. The vulnerability of the country to climate change can be offset by means of investments devoted to adaptation capacity to climate change.

Solving for the social planner's and decentralised equilibria, we find that along the optimal path, economic growth is lower when the efficiency loss in physical and human capital stock due to climate change is higher, the pollution intensity of physical capital is higher, the vulnerability of a country to climate change is higher or the adaptation efficiency of the country to climate change is lower. The long-run growth rate of income and consumption is found to be the same as that of physical capital, human capital and pollution growth rate. These results are tested empirically for a balanced panel of 62 countries including both developing and developed countries for a time spanning 1995-2016. The empirical results show that higher environmental health index (EHI), which is a proxy for higher human health and lower vulnerability of the country human capital to climate change, has a positive impact on the GDP of the country. The proxy for pollution and higher efficiency loss of investment in physical capital stock due to climate change as measured by CO_2 intensity have significant negative impact on the GDP of the country. Higher CO_2 intensity results in higher temperature and accumulation of greenhouse gases, which leads to higher frequency of environmental and physical capital damages, which, in turn reduce the efficiency of physical capital investments. These results are the same for the developing countries as well, except that CO_2 intensity has a positive impact on the GDP of the country as opposed to negative impact in case of all countries. The EHI has higher positive impact on the GDP of the country in case of developing country as measured by the associated coefficient. This offers validity to our tested hypotheses: higher the human health and lower the vulnerability of human capital to climate change higher will be the GDP of the country. The CO_2 intensity has a negative impact on GDP of the country when we consider the full sample of countries but it has a significant positive impact in case of developing country. This result implies that higher pollution levels will stimulate economic growth in developing countries. Hence low-carbon or renewable energy use and reducing fossil fuel combustion to sustain economic growth might be costly for developing countries.

To assess the differential impact of climate change on different sectors of the economy, namely agriculture, manufacturing and services, seemingly unrelated regression (SUR) estimation technique has been used to estimate the empirical model. The seemingly unrelated regression model assumes that error term is uncorrelated with each explanatory variable. If this assumption is violated than SUR estimators produce biased estimates in small samples and inconsistent estimates in large samples. Since most of the explanatory variables are exogenous in our estimation model, we resort to SUR model. Based on SUR model, we infer that improvement in human health as measured by higher EHI stimulate growth in manufacturing and services while reduces in agriculture sector. Higher CO_2 intensity negatively affects the agriculture and services sector output but has positive impact on the manufacturing sector output. Agriculture sector is the most adversely affected by the pollution Hence environmental pollution has severe negative impact on the agriculture sector as compared to manufacturing and services sectors. The structure of this paper is organized as follows. In section 2, we present the theoretical model and derive the optimal growth paths for this stylized economy, by solving the planner's equilibria, which form the basis for our empirical estimation. The empirical model framework and data sources are discussed in section 3. In section 4 the key results of the empirical estimation are presented. Section 5 concludes and discusses the policy implications of our research.

2. The Theoretical Model

The theoretical analysis helps to understand the mechanisms through which climate change affects economic growth is an adaptation of Bretschger and Valente (2011). These authors have developed an AK production function based endogenous growth model, with stock pollutants, and incorporated the effect of adaptation capacity to climate change, to derive the long run impact of climate change on growth. Since environmental pollution negatively affects human health, and health is an important part of human capital. We extend their analysis to incorporate human health impacts of pollution on investment in human capital and show that efforts to reduce pollution could possibly be viewed as an investment in human capital, and this directly affects the output growth rate.

2.1 The Analytical Framework

In the model, the output $Y(t)$ is produced by using physical capital stock, $K(t)$, and human capital stock, $H(t)$, which are combined using the following Cobb-Douglas production function of the following form:

$$Y(t) = A(t)K(t)^{\alpha}H(t)^{1-\alpha} \quad (1)$$

Let $P(t)$ denotes the change in stock of pollution at instant t, i.e., the addition of greenhouse gases in the atmosphere, and parameter $\phi > 0$ captures pollution intensity of the economy, assumed to be constant. According to equation (2), the physical capital used in the production is pollution intensive as it leads to emissions of greenhouse gases or other polluting emissions, whose concentration in the atmosphere has adverse implications for the stock of capital, which constitutes an input into production., similar to Bretschger and Valente (2011), pollution accumulation is proportional to physical capital used in production according to

$$P(t) = \phi K(t) \ . \tag{2}$$

The accumulation of greenhouse gases entails destruction of the physical capital and human capital since the economy must adapt more rapidly to ecological conditions (i.e., there is need for supplementary investments to replace existing capital stock depreciated due to climate change). Note that as the level of infrastructure/ physical capital and human health/ human capital is damaged by the level of pollution, we hypothesize that pollution growth affects the accumulation of both types of capital, and consequently reduces the efficiency of investments, which in turn, lowers the growth rate. The negative health effects of climate change hinder the transformation of human skills to human capital.

Let $\tilde{\delta}_k > 0$ and $\tilde{\delta}_H > 0$ be the baseline rate of depreciation of physical capital and human capital, respectively. Additionally, we model the quantity of physical capital and human capital damaged due to pollution by the expression $\eta_K \dot{P}(t)$and $\eta_H \dot{P}(t)$, respectively. Here, $\eta_K \ and \ \eta_H$ are the constants that measures the reduction in efficiency of physical capital and human capital investment due to poor environment. Hence, society must invest in human health, ecosystem services and infrastructure services that are crucial for environmental sustainability. The physical and human capital stocks are assumed to accumulate according to following law of motion:

$$\dot{K}(t) = I_K(t) - (\tilde{\delta}_k + \eta_K \ \phi) \ K(t), \text{ and} \tag{3}$$

$$\dot{H}(t) = I_H(t) - (\tilde{\delta}_H H(t) + \eta_H \phi K(t)) \ , \tag{4}$$

Here, I_K is gross investment in physical capital (i.e., net investment plus depreciation of physical capital attributed to climate change) and, I_H is the gross investment in human capital (i.e., net investment plus depreciation of human capital attributed to climate change).

As in Bretschger and Valente (2011), the economy might lower the impact of pollution by means of investments devoted to adaptation to climate change, denoted by *B(t).*[3] The defensive expenditure ensures that the country is able to minimize the adverse impact of climate change.[4] Here $\mathcal{E} > 0$ is a constant and measures the efficiency of the adaptation expenditure to reduce pollution. This gives rise to following dynamic equation for pollution net of adaptation,

$$\dot{\mathrm{M}}\,(\mathrm{t}) = \dot{\mathrm{P}}(\mathrm{t}) - \mathcal{E}.\,B(t). \tag{5}$$

Substituting equations (2) into equation (5), we will get dynamic law equation for pollution net of adaptation as follow:

$$\dot{\mathrm{M}}\,(\mathrm{t}) = \phi K(t) - \mathcal{E}.\,B(\mathrm{t}). \tag{6}$$

Further, the welfare of the representative individual is expressed as the present value stream of utilities, which is:

$$\mathrm{V} = \int_0^\infty U[C(t), I(t)]e^{-\rho(t)}\,dt$$

Where the felicity function has the following additive separability.

$$U[C(t), I(t)] = \ln C(t) + \alpha \ln I(t). \tag{7}$$

Here $C(t)$ is the consumption of the unique final good at time t, $I(t)$ is an index of environmental/ infrastructure services, $\alpha > 0$ is a weighting parameter attached to environmental or infrastructure services (i.e. clean water, arable land, fishing stock and transportation facilities) relative to consumption of the final, and $\rho > 0$ is the discount rate of the infinitely-lived representative individual. The utility of consumers is directly affected by environmental damages caused by greenhouse gases as clean

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[3] According to the Inter-Governmental Panel on Climate Change (IPCC), adaptation to climate change is defined as "adjustment in natural and human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities associated with climate change".

[4] It involves the expenditure on core sectors that relate to people's welfare such as health, ecosystem services, infrastructure, human habitat, food and water.

environment is positively valued by consumers. The environmental damages effect is captured by pollution induced decrease of infrastructure services.

Environmental / infrastructure services are negatively impacted by pollution net of adaptation, according to:

$$I(t) = M(t)^{-\gamma}, \gamma > 0. \tag{8}$$

Next, by substituting the equation (8) into (7), we have the instantaneous utility function,

$$U[C(t), I(t)] = \ln C(t) - \alpha\gamma \ln M(t). \tag{9}$$

The aggregate resource constraint of the economy will be:

$$Y(t) = C(t) + B(t) + I_K(t) + I_H(t). \tag{10}$$

Given the above analytical framework, we now solve for the benevolent planner's equilibrium for this stylized economy.

Substituting equation (1) into (10), we get the value of the change in physical capital stock or investment in physical capital $I_K(t)$ from (10) as:

$$I_K(t) = A(t)K(t)^{\alpha}H(t)^{1-\alpha} - I_H(t) - C(t) - B(t). \tag{11}$$

Substituting equation (11) into (3), we will get the equation of dynamics for physical capital as:

$$\dot{K}(t) = A(t)K(t)^{\alpha}H(t)^{1-\alpha} - I_H(t) - C(t) - B(t) - (\tilde{\delta}_K + \eta_k\phi)\, K(t). \tag{12}$$

2.2 Solving the Social Planner's Problem

Taking all the above, the social planner's problem can be simplified, which in turn, takes the form of dynamic optimal control problem with three state variables K(t), H(t) and M(t), and three control variables C(t), B(t) and $I_H(t)$. To solve this problem the planner maximizes function (7) subject to three constraints (12), (4) and (6); given the initial conditions $K(0) = K_0$, $H(0) = H_0$, $M(0) = M_0$.

The detailed description of planner's problem is given in Appendix II. Given the above equation expressions, the associated current value Hamiltonian expression will be:

$$\mathcal{H} = \ln C(t) - \alpha\gamma \ln M(t) + \lambda_K(t)[A(t)K(t)^{\alpha}H(t)^{1-\alpha} - I_H(t) - C(t) - B(t) - ((\tilde{\delta}_K + \eta_k\phi)\, K(t)]$$
$$+ \lambda_H(t)\,[I_H(t) - (\tilde{\delta}_H\, H(t) + \eta_H\phi K(t))] + \lambda_M(t)[\phi K(t) - \mathcal{E}.B]\,,$$

where $\lambda_K(t)$, $\lambda_H(t)$ and $\lambda_M(t)$ are the co-state variables or dynamic shadow values of the stock variables. The necessary conditions for optimality are:

$$\mathcal{H}_C = \frac{1}{C(t)} - \lambda_K(t) = 0 \qquad (13)$$

$$\mathcal{H}_B = -\lambda_K(t) - \mathcal{E}\lambda_M(t) = 0 \qquad (14)$$

$$\mathcal{H}_{I_H} = \lambda_K(t) - \lambda_H(t) = 0 \qquad (15)$$

$$\dot{\lambda}_K(t) = \rho\lambda_K(t) - \mathcal{H}_K = \rho\lambda_K(t) - [\lambda_K(t)(\alpha A(t)k(t)^{\alpha-1} - \tilde{\delta}_K - (\eta_k + \eta_H + \varepsilon^{-1})\phi)] \qquad (16)$$

$$\dot{\lambda}_H(t) = \rho\lambda_H(t) - \mathcal{H}_H = \rho\lambda_H(t) - [\lambda_K(t)((1-\alpha)A(t)k(t)^{\alpha} - \tilde{\delta}_H\,)] \qquad (17)$$

$$\dot{\lambda}_M(t) = \rho\lambda_M(t) - \mathcal{H}_M = \rho\lambda_M(t) - (-\frac{\alpha\gamma}{M(t)}) \qquad (18)$$

Taking log on both the sides of equation (23) and differentiating with respect to time, we will get that

$$\frac{C(\dot{t})}{C(t)} = -\frac{\dot{\lambda}_K(t)}{\dot{\lambda}_K(t)} \qquad (19)$$

Solving equation (26) we get the solution to the change in the co-state variable for physical capital to be:

$$-\frac{\dot{\lambda}_K(t)}{\dot{\lambda}_K(t)} = \alpha A(t)k(t)^{\alpha-1} - \tilde{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi - \rho, \qquad (20)$$

Where $k(t) = \frac{K(t)}{H(t)}$

Putting the solution of $\frac{\dot{\lambda}_K(t)}{\lambda_K(t)}$ from equation (20) into equation (19) we obtain growth rate of final good consumption as:

$$\frac{\dot{C(t)}}{C(t)} = \alpha A(t)k(t)^{\alpha-1} - \tilde{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi - \rho \tag{21}$$

Where, $\alpha A(t)k(t)^{\alpha-1} - \tilde{\delta}_K$ is marginal product of physical capital net of depreciation.

Proposition 1: *In equilibrium, the socially optimal growth rate of consumption is captured by the Euler equation for intertemporal consumption in eq. (21).*

The term $\alpha A(t)k(t)^{\alpha-1} - \tilde{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi$ in the right-hand side represents the rate of return from physical capital investment, $\alpha A(t)k(t)^{\alpha-1} - \tilde{\delta}_K$, i.e., the marginal product of capital minus the depreciation rate $\delta_{\bar{K}}$ minus the efficiency loss in physical capital stock (η_K) and human capital stock (η_H) investment due to climate change and the loss due to lack of adaptation capacity or higher vulnerability of a country to climate change (ε^{-1}).

The above proposition implies that the growth rate of a country is affected by four parameters that are associated with climate change and pollution. Economic growth is lower when (a) the efficiency loss in physical capital investment due to climate change, (η_K) , is higher, (b) the efficiency loss in human capital investment due to climate change, (η_H) , is higher, and (c) the pollution intensity of the economy (ϕ) is higher and when the vulnerability of a country to climate change (ε^{-1}) is higher or adaptation capacity to climate change is lower.

In appendix II, we derive the optimal growth paths for aggregate output, physical capital, human capital and pollution (net of adaptation) as solutions to the social planner problem, to get that:

Proposition 2: *Along the socially optimal path, aggregate output, physical capital stock, and human capital stock and pollution grow at the same rate as the rate of growth of consumption in each time period* $t \in [0, \infty)$. *Mathematically can be written as follow,*

$$\frac{\dot{C}(t)}{C(t)} = \frac{\dot{B}(t)}{B(t)} = \frac{\dot{K}(t)}{K(t)} = \frac{\dot{H}(t)}{H(t)} = \frac{\dot{Y}(t)}{Y(t)} = \frac{\dot{M}(t)}{M(t)} = \tilde{A} - \rho$$

Where $\tilde{A} = \alpha \mathrm{A(t)k(t)}^{\alpha-1} - \tilde{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi$

We next turn to the analysis of aggregate welfare in equilibrium. From equation (21) we have

$$U[C(t), I(t)] = \ln C(t) - \alpha\gamma \ln M(t).$$

By differentiating the utility function with respect to time we obtain the following time path of instantaneous welfare:

$$\frac{\dot{U}(t)}{U(t)} = \frac{\dot{C}(t)}{C(t)} - \alpha\gamma \frac{\dot{M}(t)}{M(t)} = (1 - \alpha\gamma)\frac{\dot{C}(t)}{C(t)} \tag{22}$$

Substituting equation (21) in equation (22), we obtain the growth rate of utility as follow:

$$\frac{\dot{U}(t)}{U(t)} = (1 - \alpha)\mathrm{A(t)k(t)}^{\alpha-1} - \tilde{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi - \rho, \tag{23}$$

Where $k(t) = \frac{K(t)}{H(t)}$

From equation (23) it follows that when restricting the $\alpha\gamma < 1$, a non-decreasing utility is conditional on non-decreasing consumption. That is,

$$\frac{\dot{C}(t)}{C(t)} \geq 0 \; requires \; \alpha \mathrm{A(t)k(t)}^{\alpha-1} - \tilde{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi - \rho > 0. \tag{24}$$

Proposition 3: Thus, *a non-decreasing utility is conditional on the parametric restriction that* $\alpha\gamma < 1$ in equation (23), *and a non-decreasing consumption growth captured in by. (24).*

Equation (23) implies that while invoking the parametric restriction that $\alpha\gamma < 1$, the economic growth can be sustained (that is, $\frac{\dot{U}(t)}{U(t)}$) only when the inequality in (24) is satisfied. This inequality is satisfied only if the rate of return from physical capital investment is sufficiently large as so to exceed the damages caused by climate change.

These results show that, even along the optimal path, pollution/ climate change affects both the consumption growth rate and prospects for sustainability (where sustainable growth is defined in terms of a path along which instantaneous welfare of the economy is ever increasing). When economies differ in terms of their technology, climate exposure and efficiency to adapt to climate change, we find that economies with comparatively lower technology level (and hence lower productivity) and higher physical capital to human capital ratio in the presence of pollution intensive physical capital, higher loss of human and physical capital stock to climate change, lower adaptation efficiency and higher pollution intensity of the economy are the ones that would suffer higher dynamic losses as a consequence of climate change. The importance of these findings is that these variables not only impact income levels but they also undermine the prospect for long run welfare gains for the economy. Specifically, we conclude that climate change influences the growth prospects of countries asymmetrically, and this asymmetry is biased against developing countries that are at lower levels of technological development, human capital stock and adaptation efficiency. Further, they are more exposed to the harmful effects of climate change, which put these countries in a disadvantageous position as far as sustainability of growth is concerned. In what follows, we attempt an empirical test of the above theoretical findings.

3. Empirical Analysis

Based on the literature review on climate change impact on economic growth, we expect that climate change would have significant direct adverse effects on the economic growth prospects of a country. Specifically, we have shown that by using some simple theoretical model on economic growth and environment, where growth is affected by parameters related to climate change, specifically in view of adverse consequences for countries with lower levels of technological development and human capital, more vulnerable and higher efficiency loss in human capital and physical capital investment due to climatic variations, and hence, lower capacity to develop and implement adaptation and abatement strategies. In this section, we test these propositions by using a panel of data set covering 62 countries that includes 31 developing and 31 developed countries over the period 1995-2016. In the empirical analysis, reported below, we run panel regression of the following form:

$$Y_{it} = \beta_1 + \beta_2 A_{it} + \beta_3 HC_{it} + \beta_4 PC_{it} + \beta_5 \eta_{H_{it}} + \beta_6\, \eta_{K\varepsilon_{it}} + \beta_7 \phi_{it} + \epsilon_{it} \tag{25}$$

Here, *i* represents country, *t* represents time, $Y_{it}, A_{it}, HC_{it}, PC_{it}, \eta_{H_{it}}, \eta_{K\varepsilon_{it}}, \phi_{it}$, and ϵ_{it} represents GDP growth rate, absolute level of total factor productivity index, human capital stock (measured by enrolment in secondary education), physical capital stock (estimated by perpetual inventory method) , vulnerability of human capital or human health of the country to climate change (measured by environmental health index (EHI)), CO_2 intensity (CO_2 INT) which is a proxy for pollution intensity of the country as well as the vulnerability or efficiency loss in physical capital investment , and error term respectively. Higher CO_2 intensity entails higher pollution, which, in turn leads to higher efficiency loss in physical capital investment because the country will require additional investment to replace the existing capital stock depreciated due to climate change. Similarly, lower EHI and CO_2 intensity reflect a lower adaptation capacity to climate change. To assess the impact of pollution on economic growth of the country via reduction in human capital the interaction term of human capital and CO_2 intensity (namely, HC*CO_2INT) additionally is introduced in the estimation. Given the panel dataset, both fixed effect (FE) and random effect (RE) models were fitted to run the empirical test. The Hausman test of endogeneity used to select the appropriate method of estimation between RE and FE.

It will be useful to discuss, in some detail, the variables chosen to measure the climate exposure and vulnerability of the country to climate change. According to the World Health Organization (WHO), EHI addresses all the physical, chemical, and biological factors external to a person, and all the related factors impacting behaviour. It encompasses the assessment and control of those environmental factors that can potentially affect health. Prepared by WHO, this measure is basically targeted at preventing disease and creating health supportive environment. This definition excludes behaviour not related to environment as well as behaviour related to the social and cultural environment, and genetics. As per the definition, a higher EHI of a country reflects lower exposure of human capital to climate change, which in turn, implies negative health effects. Hence, the country will experience higher economic growth via positive impact on human capital accumulation. Therefore, we expect a positive impact of higher EHI on the economic growth of a country. The EHI ranks countries on the basis of how well they perform to protect human being and their health from harmful effects of the environment. It includes indicators that are necessary for protection of human beings from climate change includes air quality, health impacts, water and sanitation.[5] See Appendix III for detailed description on EHI indicators.

We have employed CO_2 intensity as a measure of emissions intensity of the GDP. CO_2 intensity may rise or fall with GDP growth depending upon whether the GDP growth becomes de-carbonized as it grows. According to the European Environmental Agency, the total emissions of CO_2 from energy production depend on both the amount of energy produced as well as the CO_2 intensity per unit of output produced (which is also fuel specific). Therefore, policies and measures to reduce emissions of CO_2 need to address both demand (e.g. through improvements in the energy efficiency of buildings and appliances), as well as CO_2 intensity per unit of energy produced (e.g. by fuel switching, generation efficiency). Hence, higher CO_2 intensity per unit of output will imply additional investments in physical capital stock to replace the existing capital. The expected impact of CO_2 intensity on the GDP growth of the country is expected to be negative.

The empirical model is also regressed on the main sectors of the economy, such as agriculture, manufacturing and services. To capture the differential impact of the climate change on different sectors of the economy the following model is estimated:

$$Y_{ijt} = \gamma_1 + \gamma_2 HC_{it} + \gamma_3 PC_{it} + \gamma_4\, \eta_{H_{it}} + \gamma_5 \eta_{K\varepsilon_{it}} + \gamma_6 \phi_{it} + \gamma_7 UR_{it} + \gamma_8 \mathrm{POPgr}_{it} + \gamma_9 TR_{it} + \\ + \mathcal{E}_{it} \tag{26}$$

[5] For more details on indicators included in environmental health index refer to the 2012 EPI report prepared by the Yale Centre for Environmental Law and Policy available at http://epi.yale.edu.

Here Y_{ijt} is the j[th] sector of the i[th] country that is, agriculture (AG), manufacturing (MF) and services (SV), variables HC_{it}, PC_{it}, $\eta_{H_{it}}$, $\eta_{K\varepsilon_{it}}$, ϕ_{it} are the same as given in equation (25). Additionally, some control variables such as urbanisation (UR_{it}), population growth rate ($POPgr_{it}$) and trade openness (TR_{it}) are used in estimation of model (26). The proxy variables and their sources are given in Table 1. in Appendix I.

4. Results of Empirical Test

We rely on the Hausman test to select the estimation methodology, which could be either a FE or a RE model. A significant chi-square test statistic suggest that the use of a FE model would be more appropriate instead of using a RE model. In our preliminary regression, though the results of empirical estimation were in tune with theoretical analysis, our baseline econometric model suffered from both heteroscedasticity and autocorrelation. To correct for the pair-wise heteroscedasticity and autocorrelation problems, Feasible Generalized Least Square (FGLS) method was applied to country-FE model. Table 2 below shows the heteroscedasticity and autocorrelation corrected results based on a FE model specification for our base line econometric model. Two different formulations of the empirical model are tested one for all the 62 countries and the other one for the 32 developing countries.

Table 2: Country fixed effect regression model using FGLS method

Dependent Variables Log (GDP)	All Countries	Developing Countries
Independent Variables		
Constant	3.613* (0.000)	3.429* (0.000)
HC	2.69e-08* (0.000)	2.08e-08* (0.000)

PC	0.003* (0.000)	0.003* (0.000)
TFP	0.131* (0.001)	0.132* (0.002)
EHI	0.004* (0.000)	0.009* (0.005)
CO_2INT	-0.065* (0.004)	0.142* (0.005)
HC*CO_2INT	-6.90e-09* (0.000)	-5.01e-09* (0.000)
POPgr	0.032* (0.002)	0.028* (0.087)
UR	0.018* (0.000)	0.018* (0.000)
TR	0.002* (0.000)	0.001* (0.046)
GOV	0.038* (0.050)	0.121* (0.000)
F-Value	102.19	58.73

Note: the values in parenthesis are the P-value associated with Z-Statistic; * and ** denotes significance at 5% and 10% level respectively.

As can be seen in Table 2, all the independent variables included in the panel estimation have a highly significant (at 5% and 10% level of significance) impact on the GDP of the country in case of all countries and developing countries. As expected, all independent variables have positive impact on the GDP of the country except for CO_2 intensity and the interaction between human capital term and the environmental health index (EHI) in case of all countries. These results carry over for the developing countries alone, except for CO_2 intensity that has positive impact on the GDP of the country as opposed to negative impact in case of all the countries. As expected, TFP has the highest impact on the GDP of the country. Both human capital and physical capital stock also have a positive impact on GDP. EHI have positive impact, the impact is higher in case of developing country as measured by the associated coefficient. This offers validity to our tested hypotheses: higher the human health and lower the vulnerability of human capital to climate change higher will be the GDP of the country. The CO_2 intensity has a negative impact on GDP of all the countries put together but it has very high and positive impact in case of developing countries. The negative coefficient of interaction between human capital term and CO_2 intensity term reveals that environmental pollution lowers the GDP of the country through a negative impact on human capital. But, in case of developing countries, this indirect negative impact is much lower than the direct positive impact of the pollution on the GDP of the country.

Trade openness is also found to have a positive and significant impact on GDP of a country. This result is consistent with many previous empirical studies. To quote some of them, we have Romer (1993), Grossman and Helpman (1991) and Barro and Sala-i-Martin (1995) among others, who found a positive impact of trade openness on economic growth of a country. They argue that countries that are more open have a greater ability to catch up to the leading technologies of rest of the world, implying higher income growth or output. More open economies tend to grow faster than economies with trade distortion (Edward 1992, Wacziarg and Welch, 2008). Hence, greater international integration through trade is a beneficial strategy for the growth performance of a country. Population growth rate, urbanization and government effectiveness are found to have a positive impact on the GDP of the country. Customarily economists argue that population growth hinders the output growth rate yet many of them do not find consistent evidence to support this theory. We argue that higher population growth requires larger investment in infrastructure to cater to the growing population, this in turn could stimulate development and growth of the country. There are many channels through which urbanization has a positive impact on economic growth by offering opportunities for education, employment and health services. Also, countries with more effective governments experience higher economic growth by offering higher quality public services and civil services. Efficiency in the delivery of public services stimulate growth and development of the country. Countries with more effective government have effective health care and efficient education system.

The results of equation (26) of empirical model are summarised in table 3. A seemingly unrelated regression (SUR) estimation technique has been used to estimate the impact of environmental degradation on the different sectors of the economy.

Table 3. Seemingly unrelated regression (SUR) model results

Dependent Variables	Agriculture, value added (% of GDP) (AG)	Manufacturing, value added (% of GDP) (MF)	Services, etc., value added (% of GDP) (SV)
Independent Variables			
Constant	46.671* (0.000)	9.149* (0.000)	40.957* (0.000)
HC	-2.85e-07* (0.000)	-2.66e-07* (0.000)	4.67e-07* (0.000)
PC	-0.088* (0.000)	0.122* (0.000)	-0.176* (0.000)
EHI	-0.208* (0.000)	0.101* (0.000)	0.147* (0.000)
CO_2INT	-3.959* (0.000)	4.346* (0.000)	-2.235** (0.005)
HC*EHI	-3.07e-09* (0.000)	4.02e-09* (0.000)	2.03e-09* (0.04)
POPgr	0.295** (0.09)	-0.868* (0.000)	-0.953* (0.001)
UR	-0.195* (0.000)	-0.065* (0.000)	0.148* (0.000)
TR	-0.026* (0.000)	0.017* (0.000)	0.033* (0.000)
R^2	0.7967	0.2619	0.5826

Note: Values in brackets are the P-Values associated with t-statistics; * and ** denotes significance at 5% and 10%, respectively.

The results reveal that all the independent variables have a significant but varied impact across different sectors of the economy. Human capital (HC) stimulates growth in services sector (SV) while reduces growth in agriculture (AG) and manufacturing sector (MF). Physical capital (PC) stimulates growth in manufacturing while reduces in agriculture and services sector. Improvement in human health, as measured by higher EHI stimulate growth in manufacturing and services, while reduces it in agriculture sector. Higher CO_2 intensity (CO_2INT) negatively affects agriculture and services sector output but has positive impact on the manufacturing sector output. Agriculture sector is the most adversely affected by the pollution. The improvement in human health via higher environmental health stimulates human capital, which in turn, stimulates growth in manufacturing and services sector whereas it reduces growth in agriculture sector. The population growth rate (POPgr) has a negative impact on manufacturing and services sector whereas a positive impact on agriculture sector. This could be due to the fact that agriculture has the highest labour absorption capacity. Urbanisation (UR) has a negative impact on agriculture and manufacturing sector, whereas a positive impact on the services sector. Trade openness (TR) has a positive impact on services and manufacturing sector, while it has a negative impact on agriculture. This suggests that trade barriers are positively associated with growth in agriculture sector. This relationship contradicts the view of standard international trade theory which say that trade openness stimulates economic growth of the country. According to the theory of comparative advantage, trade openness leads to the efficient use of country resources through the export of goods produced by using countries abundant resources and import of goods that are too expensive to produce within country.

Environmental pollution measured by CO_2 intensity that reflect the carbon dioxide emissions from the use of burning oil, coal and gas for energy use, have the highest positive impact on the manufacturing sector output. This finding is consistent with the fact that energy consumption is necessary to produce manufacturing goods from raw materials. Carbon dioxide also enters the atmosphere from burning waste materials and wood and from some industrial processes such as cement production. While energy consumption is a vital input to the development of manufacturing sector it results in pollution which has a negative impact on agriculture and services sector output.

5. Conclusion and Policy Implications

The present study develops an extension of the one-sector human and physical capital stock model of endogenous growth, with the possibility of substitutability between the two and where both human and physical capital depreciate due to environmental pollution. The model allows for adaptation to environmental effects due to climatic variation. The theoretical model used for our analyses of climate change impacts on economic growth is an extension of Bretschger and Valente (2011). However, we go beyond the work of Bretschger and Valente (2011) to include human capital as a substitute for pollution generating physical capital stock. The socially optimal and the private optimal paths of an economy are characterized, where pollution is generated by physical capital accumulation that affects the efficiency of investment of both the types of capital. This, in turn, lowers the economic growth rate. The negative health effects of climate change hinder the development of human capital. We find that, along the optimal path, economic growth is lower when the efficiency loss in physical and human capital stock due to climate change is higher, the pollution intensity of physical capital is higher, the vulnerability of a country to climate change is higher or the adaptation efficiency of the country to climate change is lower. The long-run growth rate of income and consumption is found to be the same as that of physical capital, human capital and pollution growth rate.

The theoretical model developed is empirically tested for a balanced panel of 62 countries, including both developing and developed countries, for a time period spanning 1995-2016. The empirical results based on FGLS country fixed effect method show that higher environmental health index (EHI), which is a proxy for higher human health and lower vulnerability of the country human capital to climate change, has a positive impact on the GDP of the country. This offers validity to our tested hypotheses: the higher the human health and lower vulnerability of human capital to climate change higher will be the GDP of the country. The proxy for pollution and higher efficiency loss of investment in physical capital stock due to climate change as measured by CO_2 intensity has significant negative impact on the GDP of the country. Higher CO_2 intensity results in higher temperature and accumulation of greenhouse gases, which leads to higher frequency of environmental and physical capital damages, which, in turn reduce the efficiency of physical capital investments. The interaction term between human capital and CO_2 intensity term reveals that environmental pollution lowers the GDP of the country through a negative impact on human capital. These results are same for developing countries as well, except that CO_2

intensity now has a positive impact on the GDP of the country as opposed to a negative impact in case of all the countries put together.

To assess the differential impact of climate change on different sectors of the economy, seemingly unrelated regression (SUR) estimation technique has been used for estimation. An improvement in human health as measured by higher EHI, is found to stimulate growth in manufacturing and services, while it reduces it in case of agriculture sector. Higher CO_2 intensity negatively affects the agriculture and services sector output but has a positive impact on the manufacturing sector output. Agriculture sector is most adversely affected by pollution. The improvement in human health, via higher environmental health, stimulates human capital, which in turn, stimulates growth in manufacturing and services sector whereas it reduces growth in agriculture sector. Hence, environmental pollution has a severe negative impact on agriculture as compared to manufacturing and services sectors.

This study demonstrates that investment in environmental health (to reduce the efficiency loss of human capital) and reduction in environmental pollution (to lower the efficiency loss of physical capital investment to climate change by) is required to achieve sustainable economic growth. It seems that environment friendly investments divert resources away from more productive investments in the case of developing country. The main source of environmental pollution is supposed to be energy consumption, energy conservation requires reduction in energy consumption, which, in turn believed to hinder economic growth in case of developing countries. This calls for an arrangement in which developing countries are supported by developed countries for making such investments to adapt to the adverse effects of climate change. Investment in human capital, eco-friendly technology, human health and strengthening of vulnerable infrastructure requires availability of financial resources. Developing countries lack financial resources to make suitable investments in developing different adaptation strategies. Moreover, energy consumption is a vital input of production in the manufacturing sector, reduction in pollution via reduced emissions will have severe negative impact on the manufacturing sector of the economy. Hence transfer of funds and pollution mitigating technologies from developed countries to developing countries is a prerequisite to achieve sustainable economic growth in developing countries.

References

Akram,N. (2012). Is Economic Growth Hindering the Economic Growth of Asian Economics? Asia Pacific Development Journal, 19(2).

Barro, R. and Sala-i-Martin, X. (1995). Economic Growth, McGraw-Hill, New York.

Bretschger, L. and Valente, S., (2011). Climate Change and Uneven Development. The Scandinavian Journal of Economics, 113(4): 825-845.

Brooks and Adger, (2003). Counrty Level Risk Measures of Climate Related Natural Disaster and Implications for Adaptation to Climate Change. Tyndall Centre for Climate Change Research Working Paper 26.

Choiniere, J., and Horowitz, K. (2000). A Production Function Approach to the GDP Temperature Relationship. University of Maryl.

Collier, P., Conway, G., and Venables, T. (2008). Climate Change and Africa. Oxford Review of Economic Policy, 24, pp.211–238.

Conference Board Total Economy Database (2013). Growth Accounting and Total Factor Productivity Country Details, 1990-2012.

Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken.(2009). “Temperature and Income: Reconciling New Cross-Sectional and Panel Estimates.” American Economic Review: Papers and Proceedings, 99(2), 198–204.

Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken .(2012). “Temperature Shocks and Economic Growth: Evidence from the Last Half Century”. American Economic Journal: Macroeconomics. 4(3): 66–95.

Edwards, S. (1992). Trade Orientation, Distortions and Growth in Developing Countries. Journal of Development Economics, 39(1): 31-57.

Fankhauser, S., and Tol, R.S. (2005). On Climate Change and Economic Growth. Resource and Energy Economics, 27(1): 1–17.

Frankel, J. A. and Romer, D. (1999). Does Trade Cause Growth? American Economic Review, 89(3): 379-399.

Geffersa and Abebayehu. (2015). Impacts of Climate Volatility on Long-run Economic Growth: CrossCountry Growth Regressions. Journal of Economics and Sustainable Development, 6(15): 129-139.

Horii,R., and Ikefuji, M. (2012). Natural Disasters in a Two-Sector Model of Endogenous Growth, MPRA Paper 37825, University of Southern Denmark, Tohoku University, Yale University.

Kemal, Y.,Cuneyt, K. and Julide, K. (2009). Does Temperature Affect Labor Productivity: Cross Country Evidence, Applied Econometric and International Development, 9(1).

Kjellstrom, Tord; Kovats, R. Sari; Lloyd, Simon J.; Holt, Tom; Tol, Richard S. J. (2008). The Direct Impact of Climate Change on Regional Labour Productivity. ESRI Working Paper, No.260.

Lecocq, F., and Shalizi, Z. (2007). How Might Climate Change Affect Economic Growth in Developing Countries? Policy Research Working Paper,No. 4315. Washington, D.C.: World Bank.

Mendelsohn, R., and Dinar, A. (1999). Climate Change, Agriculture, and Developing Countries: Does Adaptation Matter? World Bank Research Observer,14(2): 277-293.

Millner and Dietz. (2011). Adaptation to Climate Change and Economic Growth in Developing Countries. Centre for Climate Change Economics and Policy, Working Paper No. 69.

Nordaus, William and Boyes, J. (2000). Warming the World: The Economics of the Greenhouse Effect. Cambridge, MA: MIT Press.

Smit, B. And Wandel, J. (2006). Adaptation, Adaptive Capacity and Vulnerability. Global Environmental Change, 16(3): 282-292.

Stern, Nicholas. (2008). “The Economics of Climate Change.” American Economic Review: Papers and Proceedings, 98(2): 1-37.

Tol, Richard, S. J. (2009). “The Economic Effects of Climate Change.” Journal of Economic Perspectives, 23(2): 29–51.

UNFCC. (2007). Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries. University of Notre Dame Global Adaptation Index Detailed Methodological Report.2013.

Wacziarg, R. and Welch, K. H. (2008). Trade Liberalization and Growth: New Evidence. World Bank Economic Review, 22(2): 187-231

.

World Bank. (2010). The Economics of Adaptation to Climate Change. World Bank, Washington, DC.

Xepapadeas, A. (2006). Economic Growth and the Environment, Ink.-G.Maler and J. Vincent (Eds.), Handbook of Environmental Economics, Elsevier, Amsterdam.

Yanikkaya, H. (2003). Trade Openness and Economic Growth: A Cross-Country Empirical Investigation, Journal of Development Economics,72(1): 57-89.

Yohe, W. and Schlesinger, E. (2002). “The Economic Geography of the Impacts of Climate Change”. Journal of Economic Geography, 2(3): 311-41.

Appendix I

Table 1: Proxy variables and their sources

Variable	**Definition**	**Source**
GDP growth rate (Y)	Gross domestic product growth rate annual (%)	World Development Indicators (WDI)
Total factor productivity (TFP)	Total factor productivity	Penn World Table (PWT) version 8.0
Human capital (HC)	Enrolment in secondary education, both sexes (number)	UNESCO Institute for Statistics
Physical capital (PC)	Capital stocks estimated using perpetual inventory method	Penn World Table (PWT) version 8.0
Environmental health index (EHI)	Environmental health index	Yale Centre for Environmental Law and Policy
Emission intensity (CO_2 INT)	CO_2 intensity (kg per kg of oil equivalent energy use)	World Development Indicators (WDI)
Agriculture (AG)	Agriculture, value added (% of GDP)	World Bank national accounts data, and OECD National Accounts data files.
Manufacturing (MF)	Manufacturing, value added (% of GDP)	World Bank national accounts data, and OECD National Accounts data files.

Services (SV)	Services, etc., value added (% of GDP)	World Bank national accounts data, and OECD National Accounts data files.
Urbanisation (UR),	Urban population refers to people living in urban areas as defined by national statistical offices.	The United Nations Population Division's World Urbanization Prospects.
Population growth rate ($POPgr$)	Estimated from total, which counts all residents regardless of legal status or citizenship.	World Development Indicators (WDI)
Trade openness (TR)	Sum of Import and export of goods and services measured as a share of GDP (%)	World Development Indicators (WDI)
Government effectiveness	Government Effectiveness measures the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. (score ranges from -2.5 to 2.5)	Worldwide governance indicators

Appendix II

Solution to the social planner's problem

Next, taking log of equation (15) and differentiating with respect to time we will get,

$$\frac{\dot{\lambda}_K(t)}{\lambda_K(t)} = \frac{\dot{\lambda}_H(t)}{\lambda_H(t)} \tag{A.1}$$

From (17) we get that the solution to the co-state variable for human capital to be,

$$-\frac{\dot{\lambda}_H(t)}{\lambda_H(t)} = \left[\left((1-\alpha)A(t)k(t)^{\alpha} - \bar{\delta}_H\right)\right] - \rho \tag{A.2}$$

Equating equation (20) to (A.2), we have

$$\alpha A(t)k(t)^{\alpha-1} - \bar{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi - \rho = (1-\alpha)A(t)k(t)^{\alpha} - \bar{\delta}_H - \rho$$

Now taking log of above expression and differentiating with respect to time considering that $\bar{\delta}_K, \phi, \eta_K, \eta_H, \rho, A$ and α are constants, we obtain that, along the optimal path, the physical capital growth rate is equal to the human capital growth rate.

$$\frac{\dot{K}(t)}{K(t)} = \frac{\dot{H}(t)}{H(t)} \tag{A.3}$$

From (18) we get the following expression

$$-\frac{\dot{\lambda}_M(t)}{\lambda_M(t)} = \frac{\alpha\gamma}{M(t\lambda_M(t)} - \rho \tag{A.4}$$

Taking log of equation (14) and differentiating with respect to time, we obtain that growth rate of both the multipliers associated with K and M is equal, that is,

$$\frac{\dot{\lambda}_M(t)}{\lambda_M(t)} = \frac{\dot{\lambda}_K(t)}{\lambda_K(t)}$$

Given this, we can use equations (20) and (A.4) to obtain the equivalence

$$\alpha A(t)k(t)^{\alpha-1} - \bar{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi - \rho = \frac{\alpha\gamma}{M(t\lambda_M(t)} - \rho \tag{A.5}$$

Now taking log of both the sides of equation (A.5) and differentiating with respect to time, we get the following expression

$$\frac{\dot{M}(t)}{M(t)} = -\frac{\dot{\lambda}_M(t)}{\lambda_M(t)} = -\frac{\dot{\lambda}_K(t)}{\lambda_K(t)} \tag{A.6}$$

Substituting the value of growth rate of dynamic multiplier for physical capital stock at instant t from equation (20) into above expression, we obtain the growth rate of pollution net of adaptation as follows

$$\frac{\dot{M}(t)}{M(t)} = \alpha A(t)k(t)^{\alpha-1} - \bar{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi - \rho \tag{A.7}$$

This implies that the growth rate of pollution net of adaptation is same as that of consumption, or

$$\frac{\dot{C}(t)}{C(t)} = \frac{\dot{M}(t)}{M(t)} \tag{A.8}$$

From (A.8) pollution net of adaptation has a same growth rate as that of consumption. Thus, one can think of a constant parameter σ equal to the ratio between consumption and pollution net of adaptation.

$C(t) = \sigma M(t)$ in each instant t (A.9)

Now dividing both the sides of equation (6) by $M(t)$ and using equation (A.9), we obtain the dynamics of $M(t)$ along the equilibrium to be:

$$\frac{\dot{M}(t)}{M(t)} = \phi\frac{K(t)}{M(t)} - \mathcal{E}\frac{B(t)}{M(t)} = \phi\sigma\frac{K(t)}{C(t)} - \mathcal{E}\sigma\frac{B(t)}{C(t)}$$

Substituting equation (A.7) into above equation, we will get

$$\alpha A(t)k(t)^{\alpha-1} - \bar{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi - \rho = \phi\sigma\frac{K(t)}{C(t)} - \mathcal{E}\sigma\frac{B(t)}{C(t)},$$

From this it follows that

$$B(t) = -\frac{(\tilde{A}-\rho)C(t)}{\mathcal{E}} + \phi\sigma\frac{K(t)}{\mathcal{E}}, \tag{A.10}$$

Where $\tilde{A} = \alpha A(t)k(t)^{\alpha-1} - \bar{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi$

Substituting the value of $B(t)$ from equation (A.10) in equation (A2) and dividing throughout by $K(t)$ yield equilibrium path to be

$$\frac{\dot{K}(t)}{K(t)} = A(t)k(t)^{\alpha-1} - \left[1 - \left(\tilde{A} - \rho\right)(\mathcal{E}\sigma^{-1})\right]\frac{C(t)}{K(t)} - \frac{I_H(t)}{K(t)} - [\bar{\delta}_K + (\eta_K + \varepsilon^{-1})\phi] \qquad \text{(A.11)}$$

Combining equation (21) with equation (A.11), the optimal proportional change in the consumption-capital ratio, denoted as $\chi(t) = \frac{C(t)}{K(t)}$, will be

$$\frac{\dot{\chi}(t)}{\chi(t)} = \frac{\dot{C}(t)}{C(t)} - \frac{\dot{K}(t)}{K(t)}$$

$$\frac{\dot{\chi}(t)}{\chi(t)} = \left(\tilde{A} - \rho\right) - A(t)k(t)^{\alpha-1} + \left[1 - \left(\tilde{A} - \rho\right)(\mathcal{E}\sigma^{-1})\right]\chi(t) + \frac{I_H(t)}{K(t)} + \bar{\delta}_K + (\eta_K + \varepsilon^{-1})\phi$$

By simplifying above expression, we get

$$\frac{\dot{\chi}(t)}{\chi(t)} = \left(\tilde{A} - \rho\right) - A(t)k(t)^{\alpha-1} + \left[1 - \left(\tilde{A} - \rho\right)(\mathcal{E}\sigma^{-1})\right]\chi(t) + \frac{I_H(t)}{K(t)} + \bar{\delta}_K + (\eta_K + \varepsilon^{-1})\phi$$

$$\frac{\dot{\chi}(t)}{\chi(t)} = (\alpha - 1)A(t)k(t)^{\alpha-1} + \left[1 - \left(\tilde{A} - \rho\right)(\mathcal{E}\sigma^{-1})\right]\chi(t) + \frac{I_H(t)}{K(t)} - (\eta_H\phi) - \rho \qquad \text{(A.12)}$$

Equation (A.12) implies that a steady-state level of $\chi(t)$ will be positive if and only if

$$1 - \left(\tilde{A} - \rho\right)(\mathcal{E}\sigma^{-1}) > 0 \qquad \text{(A.13)}$$

We further assume that equation (A.13) holds, (A.12) is stable around the sole fixed point

$$\chi(t) = \frac{(1-\alpha)A(t)k(t)^{\alpha-1} + \rho + \eta_H\phi - I_H(t)K(t)^{-1}}{1 - (\tilde{A} - \rho)(\mathcal{E}\sigma^{-1})} \qquad \text{(A.14)}$$

Substituting the value of $\chi(t) = \frac{C(t)}{K(t)}$ from equation (A.14) in equation (A.11), we have growth rate of physical capital stock as a closed form solution

$$\frac{\dot{K}(t)}{K(t)} = \alpha A(t)k(t)^{\alpha-1} - \bar{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi - \rho \tag{A.15}$$

Similarly, by dividing both the sides of equation (4) by *H(t)*, we obtain

$$\frac{\dot{H}(t)}{H(t)} = \frac{I_H(t)}{H(t)} - \bar{\delta}_H - \eta_H \phi \frac{K(t)}{H(t)}$$

Substituting the value of $\frac{I_H(t)}{H(t)}$ from equation (10) into above equation we get the expression

$$\frac{\dot{H}(t)}{H(t)} = A(t)k(t)^{\alpha} - \omega - \bar{\delta}_H - \frac{B(t)}{H(t)} - \frac{I_K(t)}{H(t)} - \eta_H \phi \frac{K(t)}{H(t)} \tag{A.16}$$

Where $\omega = \frac{K(t)}{H(t)} \Longrightarrow \frac{\dot{\omega}}{\omega} = \frac{\dot{C}(t)}{C(t)} - \frac{\dot{H}(t)}{H(t)}$, from log-differentiation.

Substituting from equations (21) and (A.16) in the above expression, we obtain

$$\frac{\dot{\omega}}{\omega} = \alpha A(t)k(t)^{\alpha-1} - \bar{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi - \rho - A(t)k(t)^{\alpha} + \omega + \bar{\delta}_H + \frac{B(t)}{H(t)} + \frac{I_K(t)}{H(t)} + \eta_H \phi \frac{K(t)}{H(t)}$$

By putting the value of ω from above equation into equation (A.16), we obtain the human capital growth rate at the equilibrium level as:

$$\frac{\dot{H}(t)}{H(t)} = \alpha A(t)k(t)^{\alpha-1} - \bar{\delta}_K - (\eta_K + \eta_H + \varepsilon^{-1})\phi - \rho \tag{A.17}$$

Now taking log on both the sides of equation (1) and differentiating it with respect to time, we get the output growth rate as follows

$$\frac{\dot{Y}(t)}{Y(t)} = \alpha \frac{\dot{K}(t)}{K(t)} - (1 - \alpha) \frac{\dot{H}(t)}{H(t)}$$

Using (A.3), we simplify the above equation to get the equivalence of the growth rate of output, physical capital and human capital stock.

$$\frac{\dot{Y}(t)}{Y(t)} = \frac{\dot{K}(t)}{K(t)} = \frac{\dot{H}(t)}{H(t)} \tag{A.18}$$

From equation (21), (A.7), (A.15), (A.17) and (A.18) it follows that consumption, net pollution, physical capital stock, human capital stock and output grows at the same rate along the equilibrium path. Therefore, we derive an optimal path characterized by balance growth path.

Appendix III

The data on environmental health (EH) index are taken from the Yale Centre for Environmental Law and Policy (YCELP), Yale University and the Centre for International Earth Science Information Network (CIESIN), Colombia University (available at www.epi.yale.edu). These data are available for the period 2000-2010 and 2012 for around 233 countries.[3] The value of the index ranges from 0 to 100, with value closer to 100 indicatives of higher environmental health. In order to prepare the EH index three categories have been considered that reflect environment related health impact on humans - environmental burden of disease, air pollution effects on humans, and water pollution effects on humans. To assess the sensitivity of human health to climate change, targets have been set to be achieved by each country in each of these specific categories, and the closer the country is to a specified target the higher is its index. The table given below shows the detailed description of categories and its indicators (Table II).

Table II: Table showing categories and indicators considered for preparing environment health index

Categories	**Indicator**	**Target**
Environmental burden of disease	Child mortality	0.0007 probability of dying between age 1& 5
Air pollution (effects on humans)	Indoor air pollution	0% of population exposed
	Particulate matter	10 ug/m3
Water (effects on human)	Access to drinking water	100% of population with access
	Access to sanitation	100% of population with access