Climate, Technological Change and Economic Growth

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Abstract
This paper investigates the incentive for developing adaptation technology in a world with changing climate within the directed technical change framework. Consistent with the market size effect, we show that technological change will tend to be biased in favour of the sector that employs the greater share of the work force over time, when the inputs are sufficiently substitutable. An economy with dominant climate sensitive sector can maintain sustained economic growth if it is capable of undertaking frontier innovations in the form of adaptation technology that increases the productivity of the inputs employed in the climate sensitive sector.

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JEL Classification*:* O31; O32; O33; O44; Q55

1. **Introduction**

An increasing number of observers and policy makers have been signaling public concern to the existence of serious environmental dangers associated with economic growth. First, economic growth precipitates the depletion of exhaustible energy resources. If these resources are essential in production of final goods, then the current path of growth and development is unsustainable. Second, economic growth induces deterioration of the environment through carbon dioxide emissions that may gravely damage production and life on earth. In response to the first concern, some environmentalists far back in the 1970s opined that bringing economic growth to a halt is the only sustainable long-run objective. A popular response to the second concern is the Al Gore movie, *An Inconvenient Truth,* and the Stern Report (2006) on the economic costs of not reducing carbon dioxide emissions. These have contributed to the turning of the issue into top headlines, and have prompted government heads in the G8, and international organizations such as the UN to act quickly on it.

A change in the global climate has been seen by many as a key threat to long-run economic growth. Many potential channels of transmission have been identified both theoretically and empirically, and a negative growth effect from climate change is not a conclusive one. Following the oil price shocks in the 1970s, the world entertained such fears with regards to the world exhausting its supply of energy resources. However, technological innovation has almost removed the fear of energy exhaustions. The interesting question that this paper asks is whether technological change will make nonsense of the fear that climate change will halt worldwide economic growth and hamper poverty reduction efforts in the developing world. Since countries and regions differ in terms of their ability to develop and adopt new technology, the impact of climate change on economic growth will differ across the regions of the world. Even in the world of equal access to existing technology, differences in factor endowments will imply differences in the impact of climate change across regions, unless technological change is neutral (benefits all factors of production equally) and the share of the climate sensitive sector in aggregate output is equal across regions of the world. None of these conditions is likely to hold in practice. The obvious implication is that climate change will affect world income distribution, it will hurt some countries more than others.

There is a fast growing literature investigating the impact of climate change and economic growth, theoretically and empirically (see for instance: Frankhauser and Tol, 2005; Nordhaus, 2006; Mendelsohn, 2009; Dell et al, 2009; Milliner and Dietz, 2011; Acemoglu, et al, 2012, Alagidede et. al, 2014). The key conclusion from Frankhauser and Tol (2005) is that climate change (temperature increases) has negative effect on saving rate and hence capital accumulation. If one has some trust in neoclassical and AK type models of growth, then the conclusion from this finding by Frankhauser and Tol (2005) is that climate change is bad for growth. Milliner and Dietz (2011) argued that the dichotomy between adaptation investment and growth on one hand, and mitigation investment and development on the other is ambiguous. They concluded that the task of apportioning investment between productive capital and adaptation investment is a subtle one. What matters for growth is aggregate investment, hence as the economy develops, it automatically insulate itself from the adverse impacts of climate change. This prediction is a bad news to poor countries.

The evidence from the empirical literature on the effect of climate change is a mixed one. Nordhaus (2005) found a negative relationship between temperature (a proxy for climate change) and output per capita but a strongly positive relationship between temperature and output per area (country size adjusted GDP). Another interesting finding reported by Nordhaus is that geographic factors account for much of the income differences between Africa and the rest of the world. The G-Econ database provided a better estimates of the economic impact of greenhouse warming than has been reported in previous studies. First, rising temperature significantly reduce economic growth in poor countries, but such effect is insignificant in developed countries. Second, higher temperatures appear to decrease growth rates in poor countries than just the level of output. Third, increases in temperature have wide-ranging effects on poor countries, reducing agricultural output, industrial output and aggregate investment and political instability. These findings reported by Dell et. al (2008) suggest that the effect of climate change at the aggregate level depends on a country's level of development, with the negative effect damped as the country moves up on the development ladder. This implication is consistent with the implications of the theoretical conclusion by Milliner and Dietz (2011) that economic development will automatically insulate countries from the perils of climate change and thus a separate adaptation investment from productive capital accumulation may not make much difference. With regards to precipitation, Dell et. al. (2008) concluded that precipitation does not have any significant effect on economic growth. This conclusion is independent of a country's level of development. In a related study, Dell et. al. (2009), combined theory with empirics to further examined the temperature income relationship. Employing data from 12 countries in the Americas, Dell et. al. (2009) establishes negative cross-sectional inter and intra country relationship between temperature and income. However, as the authors argue, about half of the negative short run effects of temperature on growth are mitigated through long run adaptation.

The present paper contributes to the theoretical debate on the impact of climate change on economic growth. Similar to Acemoglu et al (2012), we examine the impact of climate change on economic growth using the Acemoglu (2002) as a template. There are two broad responses of technological change to climate change: mitigation versus adaptation technologies. Acemoglu, et. al. (2012), focused on the former. Using the directed technical change framework, they argue for mitigation approach technology to contain the perils of climate change and optimal policies to support this approach (taxing dirty technology and subsidizing clean technology). This paper moves beyond mitigation strategy to containing the menace of climate change for at least two reasons. First, mitigation strategies require a concerted global effort and hence are likely to fail because of the free-rider incentives and the long delay in reaching agreement. Second, the global climate is already in the change process and hence copping strategies through technological innovations is necessary to contain the adverse effects of climate shocks. However, we are by no means arguing for adaptation technology as a substitute to mitigation, but in complementarity. The present paper focuses on adaptation technology. We thus focus on how endogenizing the rate and the direction of technological change in a world of changing climate can reduce the negative impacts of climate change. Thus, is there any hope for sustained growth if the preventive/mitigation strategy proposed by Acemoglu 2012 fails? This paper argues that the response to this question depends on the direction of technological change in favour or against the climate sensitive sector. If the climate sensitive sector is large and technological change is biased towards the sector, then growth can be sustained in the long run. On the contrary, if technological change is biased against the climate sector, growth will be slowed and poverty and deprivation will accelerate for an economy with a relatively large climate sensitive sector. This will make climate impact on growth differ across the regions of the world, with countries capable of undertaking frontier innovations escaping the perils of climate change, even if the climate sector is large. This paper therefore provides a formal economic theoretic framework to the 'prophesy' that poor countries will receive a lion's share of climate change, at least in terms of the economic impacts.

The rest of the paper is organized as follows. Section 2 presents the basic framework for the investigation using Acemoglu 2002 as a template. Section 3 investigates the equilibrium of the model under constant technology. In section 4, we allow both the rate and the direction of technical change to be endogenous and examine its implication for growth in an economy with a climate sensitive sector. Section 5 concludes the paper.

2. The Model

This section of the paper describes the economic environment and the interactions among economic agents within this environment. First, we consider the optimizing behaviour of a representative household with infinitely planning horizon. We then turn to the maximization problem facing final good firms as well as intermediate good producers. Following Acemoglu (2002), we assume that there are two sectors, climate sensitive sector (*C-sector*) and non-climate sensitive sector (*N-sector*), producing intermediate output which serve as inputs to final good firms. Finally, we consider the maximization problem facing innovators/technology firms. The output of the technology firms are used in the intermediate sector as inputs. Following Acemoglu (2002), we simply call the output of the technology sector machines. A key assumption of the paper is that climate change (in the form increasing mean temperature and declining and changing pattern of rainfall) reduces the productivity of the factors of production employed in the climate sensitive sector, but not in the non-climate sensitive sector.

2.1 The consumers

We assume that the economy is populated by identical and infinitely-lived households with constant relative risk-aversion preferences. The households derive utility from consumption *Z*and supply labour inelastically. Households are employed in one of three sectors: climate sensitive (e.g. agriculture and related activities); non-climate sensitive (manufacturing/industrial and services related activities)and as laboratory scientists (*R&D* related activities) sectors. The total population of the economy is given by $L = L_C + L_N + L_R$; where L_C and L_N are the number of workers in the climate sensitive and non-climate sensitive sectors respectively and L_R is the number of scientists who work in the *R&D* sector. Assuming constant population at the moment, the utility function of the representative household is:

$$U(Z) = \int_0^\infty \frac{Z^{1-\theta} - 1}{1-\theta} e^{-\rho t} dt \qquad (1)$$

where ρ is the rate of time preference and θ is the inverse of the intertemporal elasticity of substitution (or the elasticity of marginal utility of consumption). To simplify notations, we suppress the time argument in the utility function and will do so throughout as long as this causes no confusion. The output of the final good is allocated between consumption, investment and research and development (R&D) expenditure. Thus, the aggregate resource constraint of the economy is;

$$Y \geq Z + I + R \tag{2}$$

where Y is the aggregate output of the final good sector (GDP), I is total investment (expenditure on machines by intermediate input producers) and R is total R&D expenditure. We also impose the usual no-Ponzi game condition, requiring the lifetime budget constraint of the representative consumer to be satisfied. More specifically, the representative household maximizes (1) subject to the following asset accumulation equation.

$$\dot{B} = rB + \gamma_1 w_C L_C + \gamma_2 w_N L_N + (1 - \gamma_1 - \gamma_2) w_R L_R - Z \tag{3}$$

where B is the total household assets, r is the interest rate, γ_1 is the share of household members who work in the climate sensitive sector, w_C is the wage for workers employed in the climate sensitive sector; γ_2 is the share of household members who work in the non-climate sensitive sector, w_N is the wage for workers in the non-climate sensitive sector. Also, w_R is the wage for the workers in the *R&D* sector. The usual intertemporal utility maximization problem gives the standard consumption Euler equation in (4).

$$\frac{\dot{Z}}{Z} = \frac{1}{\theta}(r - \rho) \tag{4}$$

The expression in (4) is also the aggregate growth rate of the economy since at the steady state, aggregate output and consumption must grow at a common rate. Along the balanced growth path, the growth rate of the economy depends on the market interest rate and preference parameters. A higher interest rate makes the steady state growth rate of the economy higher, all things being equal. However, the rate of time preference and the elasticity of marginal utility of consumption (the inverse measure of the elasticity of substitution) have depressing effects on the steady state growth rate.

2.2 Final Good Production

Final good producers are competitive and the unique final good is produced with a CES aggregate of the outputs of the two intermediate good sectors: climate sensitive sector (*C-sector*) and non-climate sensitive sectors (*N-sector*). For concreteness, consider the *C-sector* as agriculture and agriculture related activities and the *N-sector* as manufacturing/industrial and services activities. Additionally, we assume that machines depreciate fully after use. A key assumption that will play a crucial role in this paper is that some machines can only complement the inputs in the climate sensitive sector while some other machines can only complement the inputs in the non-climate sensitive sector. Thus, the relative productivity of technology (machine) depends on the sector in which it is employed.

2.3 Maximization problem for final good producers

We begin our analysis here with production and maximization problem facing the firms in the final good sector. The unique final good is assumed to be produced with a CES production function of the form:

$$Y = \left[\lambda_C Y_C^{\frac{\varepsilon-1}{\varepsilon}} + \lambda_N Y_N^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}}, \tag{5}$$

where Y_C is the intermediate inputfrom the *C*-sector and Y_N is the intermediate inputfrom the *N*-sector, $\varepsilon \in (0,\infty)$ is the elasticity of substitution between these two inputs in the production of the final good. If $\varepsilon > (<)\, 1$, then the outputs of the *C*-sector and the *N*-sector are gross substitutes (complements) in the production of the final good. Also, λ_C and λ_N (with $\lambda_C + \lambda_N = 1$) are the distribution parameters that measure the relative importance of the two intermediate inputs from the two sectors in final good production. Without loss of generality, we normalize the price of the final good at unit. This normalization implies:

$$\left[\lambda_C^{\varepsilon} P_C^{1-\varepsilon} + \lambda_N^{\varepsilon} P_N^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}} = 1$$

where the left hand side is the unit cost of production.

The normalization of the price of the final good together with the assumption that final good firms face competitive factor and product markets imply the following maximization problem for final good producers:

$$\max \Pi = Y - P_C Y_C - P_N Y_N$$

Taking the first order conditions and rearranging, we obtain the following expression for the relative price of the *N-sector*

$$\frac{P_N}{P_C} = \frac{\lambda_N}{\lambda_C} \left[\frac{Y_N}{Y_C} \right]^{-\frac{1}{\varepsilon}} \tag{6}$$

The expression in (6) is the usual relative inverse demand curve with a negative slope as expected. According to equation (6), the relative price of the output of the *N-sector* is a decreasing function of the relative output of the sector. The relative importance of the sector's output (which serve as an input in final good production), makes its relative price higher.

2.3 Maximization problem of Intermediate goods producers

We now move from the final output to intermediate input production. The output of the *C*-sector is produced with a fraction of thelabour (L_C)and a continuum of climate sector complementary machines x_C in the $(0, A_C]$ interval. Climate sector technology can take one of many forms: irrigation technology, drought resistant crop variety, drought resistant livestock variety, etc. To allow for variety of interpretations, we do not specify the exact nature of the adaptation technology.In order to solve the model analytically, we use the Dixit-Stiglitz constant elasticity structure for the productions in the intermediate goods sector. We thus have the following production function for the *C*-sector.

$$Y_C = \frac{L_C^{\alpha}}{1-\alpha} \int_0^{A_C} x_C(i)^{1-\alpha} di \tag{7}$$

Similarly the production function for the *N*-sector is written as:

$$Y_N = \frac{L_N^{\alpha}}{1-\alpha} \int_0^{A_N} x_N(i)^{1-\alpha} di \tag{8}$$

Here, A_C and A_N capture the states of *C*-sector complementary and *N*-sector complementary technologies respectively. *C*-sector complementary technologies increases the physical productivity of the inputs employed in the climate sensitive sector and hence the output of the climate sector whereas *N*-sector complementary technologies increases the physical productivity of the workers and other inputs used in the non-climate sensitive sector and hence the output of the manufacturing and the services sectors.

The maximization problem facing the firms in the climate-sensitive sector can be stated as:

$$\max P_C Y_C - w_C L_C - \int_0^{A_C} q_C(i) x_C(i) di$$

where q_C is the price of *C*-sector complementary machines, all other variables are as already defined. The first order conditions for maximization are:

$$w_C = \frac{\alpha}{1-\alpha} P_C L_C^{\alpha-1} \int_0^{A_C} x_C(i)^{1-\alpha} di = \alpha \frac{P_C Y_C}{L_C} \quad (9)$$

$$P_C L_C^{\alpha} x_C(i)^{-\alpha} - q_C(i) = 0 \quad (10)$$

Equation (10) can be rearranged to obtain the demand for machine type *i* used in the resource sector as

$$x_C(i) = \left(\frac{P_C}{q_C(i)} \right)^{\frac{1}{\alpha}} L_C \quad (11)$$

As it is common in the literature on endogenous technological change (see for instance Aghion and Howitt, 1992; 2009), we assume that each intermediate firm uses only one type of machine.

We now turn to the maximization problem facing the intermediate firms in the manufacturing sector. The maximization problem is stated as follows:

$$\max \pi_N = P_N Y_N - w_N L_N - \int_0^{A_N} q_N(i) x_N(i) di$$

Following the same procedure as in the climate sector we obtain the following expressions as factor demand functions for the manufacturing and services sectors.

$$x_N(i) = \left(\frac{P_N}{q_N(i)} \right)^{\frac{1}{\alpha}} L_N \quad (12)$$

$$w_N = \frac{\alpha}{1-\alpha} P_N L_N^{\alpha-1} \int_0^{A_N} x_N(i)^{1-\alpha} di = \alpha \frac{P_N Y_N}{L_N} \quad (13)$$

Note the isoelastic nature of the demand for machines in both the climate and non-climate sectors of the economy as presented in equations (11) and (12). The implication of isoelastic machine demand functions in the two sectors is that each technology monopolist sets a constant markup over marginal cost.According to equation (11), the demand for climate sector complementary machines depends on three factors: the price of the output of the climate sensitive sector, the price of climate sector complementary machines and the number of unskilled labour employed in the climate sensitive sector. Consistent with the law of demand, the demand for machines used in the climate sector is a decreasing function of its own price, all things being equal. However, the larger the size of unskilled labour, the higher the demand for climate sector complementary machines. Since unskilled labour complements climate sector machines, larger supply of unskilled labour raises the productivity of machines used in the climate sensitive sector, thereby increasing its demand. As expected, the higher the price of the output of the climate sensitive sector the higher the demand for machines used in the sector, all things being equal. Similarly, equation (12) indicates that the demand for *N-sector* complementary machines decreases in its own price; but increases in the size of skilled labour force and the price of the output on the sector.

The wage for the workers employed in a particular sector is equal to the value of their marginal contribution to the production of intermediate inputs in that sector, according to equations (9) and (13). This result about wage setting follows from basic microeconomic principles, on the assumption that the labour market is competitive.

2.4 Maximization problem facing innovators

As a final step, we consider the profit maximization problem facing innovators in the economy. The price of machines, $q(i)$, is chosen by the entrepreneur/innovator to maximize profits. Assume that the marginal costs of building a machine is the same across sectors and is given by χ. Each entrepreneur sells machines at the monopoly price by maximizing profit subject to the demand for machines. For the *C*-sector, we have the maximization problem facing the technology monopolist as

$$\max \pi_C = x_C(i)[q_C(i) - \chi]$$

Substituting for $q_C(i)$ using equation (10) we obtain the following expression for the price of the machines that is valid for the manufacturing and services sectors as well.

$$q_C(i) = q_N(i) = \frac{\chi}{1-\alpha} \qquad (14)$$

Following Acemoglu (2002), we set $\chi = 1-\alpha$, which simplifies the notation without any loss of generality. This and the previous condition on machine prices in (14) imply that the profit maximizing price of machines is equal to one unit of the final good. The implication of this is that one unit of machine employed by either sector is exchanged one for one with the final good.

3. **Equilibrium under Constant Technology**

We now examine the equilibrium of our model under constant technology assumption. We begin by substituting the equilibrium price of machines (which is one unit of the final good) into the machine demand functions in (11) and (12). This exercise yields the following equilibrium expressions for machine demand functions.

$$x_C(i,) = P_C^{\frac{1}{\alpha}} L_C \qquad \text{and} \qquad x_N(i) = P_N^{\frac{1}{\alpha}} L_N \qquad (15)$$

The equilibrium expressions for machine demand functions in equation (15) imply that the equilibrium quantities of machine demand do not depend on the identity of the machine. What matters is the sector in which the machine is used (the price of the sector's output and the size of the workers employed by the sector). The implication from this finding is that profits are also independent of machine variety. Substitution of equation (15) into the maximization problem of innovators gives the following equilibrium profit expressions for technology firms in equation (16) under constant technology.

$$\pi_C = \alpha P_C^{1/\alpha} L_C \qquad \text{and} \qquad \pi_N = \alpha P_N^{1/\alpha} L_N \qquad (16)$$

What is relevant for the monopolist decision to establish a research laboratory is not the instantaneous profits, but the net present discounted value of profits. These net present discounted values can be expressed in Hamilton-Jacobi-Bellman form:

$$r(t)V_C - \dot{V}_C = \pi_C \qquad \text{and} \qquad r(t)V_N - \dot{V}_N = \pi_N$$

Where $r(t)$ is the interest rate which is potentially time varying. The above equations relate the present discounted value of profits, V, to the flow profits, π. The $\dot{V}$ term in the Hamilton-Jacobi-Bellman equation takes care of differences in current and future profits resulting changing prices (a measure of capital gain or losses). Along the balanced growth path, $\dot{V} = 0$. This implies the following expressions for the discounted value of future profits:

$$V_C = \frac{\pi_C}{r} = \frac{\alpha P_C^{1/\alpha} L_C}{r} \qquad \text{and} \qquad V_N = \frac{\pi_N}{r} = \frac{\alpha P_N^{1/\alpha} L_N}{r}$$

The greater is V_N relative to V_C, the greater the incentive to develop *N-sector* complementary technologies. Inspection of the above expressions indicated that the direction of technological change is driven by two forces: relative prices (the price effect[2]) and relative supply of labour (market size effect[3]).

[2]There is greater incentive to invent technologies producing expensive goods, as is shown by the fact that V_C and V_N are increasing in P_C and P_N.

[3] A larger market size for technology leads to more innovation. Since the market size of technology consists of the workers who use it, the market size effect encourages innovation for the largest sector of the economy (the sector that employs the larger share of the labour force).

We now combine the equilibrium demand functions for machines in equation (15) and the intermediate input production functions in equations (7) and (8) to obtain the "derived" production functions for the two intermediate goods.

$$Y_C = \frac{1}{1-\alpha} P_C^{\frac{1-\alpha}{\alpha}} A_C L_C \tag{17}$$

$$Y_N = \frac{1}{1-\alpha} P_N^{\frac{1-\alpha}{\alpha}} A_N L_N \tag{18}$$

Equations (17) and (18) indicate that the equilibrium quantity of intermediate input produced in a sector depends positively on the price at which the input produced in the sector is sold to final good producers; the current state of technology used in the sector; and the size of the workers employed in the sector.

It is important to see how one unit of the intermediate input of the climate sensitive sector exchanges for intermediate input of the non-climate sensitive sector. To achieve this, we substitute equations (17) and (18) into equation (6) to obtain

$$\frac{P_N}{P_C} = \left(\frac{\lambda_N}{\lambda_C}\right)^{\frac{\varepsilon\alpha}{\sigma}} \left(\frac{A_N}{A_C}\right)^{-\frac{\alpha}{\sigma}} \left(\frac{L_N}{L_C}\right)^{-\frac{\alpha}{\sigma}} \tag{19}$$

where $\sigma = 1 + (\varepsilon - 1)\alpha$ is the derived elasticity of substitution between the inputs in intermediate goods production. Note that $\sigma > 1$ if and only if $\varepsilon > 1$. That is, the two kinds of labour inputs are gross substitutes only if the two intermediate goods are gross substitutes in final good production. Interestingly, the relative importance of the intermediate input for the *N-sector* in final good production raises the relative price of the intermediate input from the sector. However, the technological gap between the two sectors and the relative size of labour in the *N-sector* make the relative price of the *N-sector* lower, all things being equal.

Similarly, we compute an expression for the relative wage by first combining equations (9) and (13) and substituting (17), (18) and (19) into the resulting expression. This gives the following equilibrium expression for the relative wage under constant technology.

$$\frac{w_N}{w_C} = \left(\frac{\lambda_N}{\lambda_C}\right)^{\frac{\varepsilon}{\sigma}} \left(\frac{A_N}{A_C}\right)^{\frac{\sigma-1}{\sigma}} \left(\frac{L_N}{L_C}\right)^{-\frac{1}{\sigma}} \tag{20}$$

According to equation (13), the relative importance of the output of the *N-sector* in the production of the final good makes the wage of the workers in the non-climate sensitive sector higher. The impact of the technological gap between the two sectors on the relative wage is ambiguous; the effect depends on how the derived elasticity of substitution compares with one. If the derived elasticity of substitution is larger than one (factors are gross substitutes), then technological gap between the two sectors increases the relative wage in favour of the workers in the non-climate sensitive sector. On the other hand, if the factors are gross complements (derived elasticity of substitution is less than one), then technological gap between the two sectors will tend to have equalizing effect on the relative wage. The relative supply of workers in the *N-sector* has a depressing effect on wage inequality between the workers in the climate sector and non-climate sensitive sectors.

Finally we solve for the equilibrium expression for relative profitability, under constant technology assumption. We obtain this by combining equations (16) and (19).

$$\frac{\pi_N}{\pi_C} = \left(\frac{\lambda_N}{\lambda_C}\right)^{\frac{\varepsilon}{\sigma}} \left(\frac{A_N}{A_C}\right)^{-\frac{1}{\sigma}} \left(\frac{L_N}{L_C}\right)^{\frac{\sigma-1}{\sigma}} \tag{21}$$

Unambiguously, the relative importance of the output of the *N-sector* in the production of the final good increases the relative profitability of developing *N-sector* complementary technology. On the contrary, the current state of technological gap between the two sectors reduces the relative profitability of developing *N-sector* complementary technology. The effect of relative factor supply on relative profitability is ambiguous; it depends on the size of the derived elasticity of substitution between the worker in the climate and non-climate sensitive sectors. If the derived elasticity of substitution is larger than one (the two factors are gross substitutes), then relatively larger supply of labour in the *N-sector*increases the relative profitability of developing*N-sector* complementary technology. On the other hand, if the two factors are gross complements, then relatively larger supply of labour in the *N-sector* reduces the relative profitability of developing *N-sector* complementary technology.

4. Equilibrium under Endogenous Technology

Having considered the equilibrium of the model under the assumption that the level and bias in technology is constant, we now consider how by allowing for the rate and the direction of technological change to be endogenous affects the predictions of the model. We adopt a variant of the knowledge-based *R&D* specification of the innovations possibility frontier. To ensure sustained economic growth, we assume that current researchers stand on the shoulder of giants, which guarantees that the marginal productivity of research does not decline over time. Following Acemoglu (2002), we assume that *R&D* is carried out by scientists and there is a constant supply of scientists equal to L_R. To allow for knowledge spillovers while eliminating scale effects, we follow Jones (1995, 1999, 2005) and specify the innovations possibility frontiers with limited state dependence as:

$$\dot{A}_C = \mu_C A_C^{\phi} L_{RC}, \qquad \text{and} \qquad \dot{A}_N = \mu_N A_N^{\phi} L_{RN} \tag{22}$$

where $0 < \phi \leq 1$ and $L_{RC} + L_{RN} = L_R$. In the case of $\phi = 1$, the popular knowledge-based specification of the innovations possibility frontier applies, but with extreme state dependence. On the other hand, when $\phi < 1$, the extent of knowledge spillovers from past research islimited, and the economy does not have steady growth in the absence of population growth.

With this formulation of the innovations possibility frontier, the free-entry conditions for innovating in one of two *R&D* sectors are given by the following:

$$\begin{aligned} &\mu_C A_C^{\phi} L_{RC} V_C \leq w_R \\ &\mu_C A_C^{\phi} L_{RC} V = w_R \qquad \text{if} \qquad L_{RC} > 0 \end{aligned} \tag{23}$$

and

$$\begin{aligned} &\mu_N A_N^{\phi} L_{RN} V_N \leq w_R \\ &\mu_N A_N^{\phi} L_{RN} V_N = w_R \qquad \text{if} \qquad L_{RN} > 0 \end{aligned} \tag{24}$$

With this type of specification, assuming that total population (including the population of scientists) grows at an exponential rate n, one can show that per capita output of the economy grows at the rate $g^* = n/(1-\phi)$ when $0 < \phi < 1$.

Following Acemoglu (1998; 2002; 2009), the focus of this paper is to analyze how the relative sizes of the markets for climate sensitive to non-climate sensitive sectors of the economy affects the direction of technical change. When the free entry conditions in (23) and (24) are both satisfied, balanced growth (steady state) technology market clearing condition implies:

$$\mu_C A_C^{\phi} \pi_C = \mu_N A_N^{\phi} \pi_N , \quad (25)$$

where ϕ captures the importance of state dependence in the technology market clearing condition, and profits are time invariant, since they refer to balanced growth values, which are constant.

Equation (25) implies the following expression for relative profitability of innovating in the non-climate sensitive sector of the economy.

$$\frac{\pi_N}{\pi_C} = \left(\frac{\mu_N}{\mu_C}\right)^{-1} \left(\frac{A_N}{A_C}\right)^{-\phi} \quad (26)$$

Substitution of equation (21) into equation (26) gives the equilibrium relative technology as:

$$\frac{A_N}{A_C} = \left(\frac{\mu_N}{\mu_C}\right)^{\frac{\sigma}{1-\phi\sigma}} \left(\frac{\lambda_N}{\lambda_C}\right)^{\frac{\varepsilon}{1-\phi\sigma}} \left(\frac{L_N}{L_C}\right)^{\frac{\sigma-1}{1-\phi\sigma}} \quad (27)$$

Equation (27) is the key results of the directed technical change literature. According to (27), the technological gap between the *N-sector* and the *C-sector* decreases in the relative cost of developing *N-sector* complementary machines if $1-\phi\sigma > 0$. The relative importance of the *N-sector* in the production of the final good has similar effect on the direction of technical change under this condition. If σ is sufficiently large (high degree of substitution between the production factors) so that $\phi\sigma > 1$, then the above effects on the direction of technical change are reversed.

More importantly, an increase in the relative supply of labour to the non-climate sensitive sector increases the technological gap in favour of the non-climate sensitive sector if $1-\phi\sigma > 0$ and $\sigma > 1$. With $\sigma > 1$, the production factors are gross-substitutes and hence increase in technological gap in favour of the *N-sector,* whichimplies *N-sector* biased technical change. On the other hand, if $1-\phi\sigma > 0$ and $\sigma < 1$, then an increase in the supply of labour in the *N-sector* relative to the *C-sector* causes an increase in *C-sector* complementary technology there by lowering the technological gap between the two sectors. However, with $\sigma < 1$ as we have assumed, the production factors are gross complements, hence the direction of technical change in favour of the *C-sector* is biased in favour of the *N-sector*. Thus technological change, under reasonable assumptions, tends to favour the production factors employed in the larger sector of the economy. This is the market size effect emphasized in Acemoglu (1998, 2002).

We now examine the implications of endogenous directed technical change for the relative wage. To do this we substitute equation (27) into equation (20). This exercise gives:

$$\frac{w_N}{w_C}=\left(\frac{\mu_N}{\mu_C}\right)^{\frac{\sigma-1}{1-\phi\sigma}}\left(\frac{\lambda_N}{\lambda_C}\right)^{\frac{\varepsilon(1-\phi)}{(1-\phi\sigma)}}\left(\frac{L_N}{L_C}\right)^{\frac{\phi+\sigma-2}{1-\phi\sigma}} \tag{28}$$

From equation (8) the effect of the relative supply of labour in the non-climate sensitive sector has an ambiguous effect on the relative wage. An increase in the relative supply of labour in to the *N-sector* increases the relative wage in favour of the workers in that sector if $1-\phi\sigma>0$ and $\sigma>2-\phi$. This implies the possibility of having an upward sloping factor demand curve when the direction of technical change is biased in favour of the sector. This result is consistent with the *strong induced bias hypothesis* of Acemoglu (1998; 2002).

It is also interesting to find out how the endogeneity of the rate and the direction of technological change affect relative profitability between the two *R&D* sectors. Since the direction of technological change is endogenous, we must substitute equation (27) into equation (26) to obtain the steady state relative profitability ratio.

$$\frac{\pi_N}{\pi_C}=\left(\frac{\mu_N}{\mu_C}\right)^{-\frac{1}{1-\phi\sigma}}\left(\frac{\lambda_N}{\lambda_C}\right)^{-\frac{\varepsilon\phi}{1-\phi\sigma}}\left(\frac{L_N}{L_C}\right)^{-\phi\frac{\sigma-1}{1-\phi\sigma}} \tag{29}$$

The expression in (29) reveals some interesting results. The relative profitability of innovating in the *N-sector* decreases in the cost of innovating in the sector relative to the *C-sector*if $1-\phi\sigma>0$. Similarly, the relative importance of the *N-sector* in the production of the final good make relative profitability of innovating in the sector lower when $1-\phi\sigma>0$. These effects are reversed when the degree of substitution between the production factors is sufficiently high (a high σ) so that $1-\phi\sigma<0$. When $\sigma>1$ and $1-\phi\sigma>0$, an increase in the relative supply of labour into the *N-sector* decrease relative profitability of innovating in the sector. When the production factors are gross complements, however, relative profitability will be higher in the sector that employs a greater share of the labour force.

5. Concluding thoughts

This paper examined the conditions under which climate change may be harmful for long-run growth in an economy with climate sensitive sector such as agriculture and related activities. Specifically, in this paper we introduced endogenous and directed technical change in a growth model for an economy that depends on both climate and non-climate sensitive sectors. The main conclusion of the paper is that there is a tendency for technological change to be biased towards the inputs employed in the dominant sector (in terms of employment of labour) of the economy. In an economy in which the climate sector employs a larger share of the labour force, technological change will be biased towards the sector and thus raises the relative marginal product of the inputs employed in the climate sector, if the inputs are sufficiently substitutable.On the other hand, if the climate sector is the least employer of labour in the economy, then innovators will direct their efforts towards the development of technology that complements the factors employed in the non-climate sensitive sector. If the elasticity of substitution between the factors employed in the two sectors is sufficiently large, this development implies bias in technology in favour of the factors employed in the non-climate sensitive sector. In the case where the inputs are complementary, *N-sector* complementary technology is bias towards the inputs in the *C-sector* in the sense that *N-sector* complementary technology raises the relative marginal productivity of the factors employed in the climate sensitive sector.

The implication of this finding is that growth can be sustained in a world with changing climate when the degree of substitution between the production factors is sufficiently strong. In an economy with large climate sector, the development of climate sensitive sector complementary technology will more than offset the decline in productivity of the factors employed by the sector and thus offset any adverse growth effect from climate change. On the other hand, if the climate sector is the least employer of labour, then technology will tend to be bias towards the non-climate sensitive sector, thereby raising the productivity of the inputs in that sector. The increase in the productivity in the dominant sector will more than offset any productivity declines emanating from changing climate.

The conclusions from this paper imply that it is not the dominance of the climate sector *per se* that makes climate change potentially bad for growth. Rather, it is the ability of an economy to innovate at the world technology frontier, and the extent of complementarity and substitutability between the two sectors. An advanced economy capable of undertaking frontier innovations will have its rate of economic growth and development least affected by climate change, even if the climate sector is sufficiently large. On the contrary, a poor country witha large climate sector may have its rate of growth affected significantly by climate change due to its inability to undertake frontier innovations. A poor country would suffer more from climate because of the climate sensitive sector use of inferior technology, the main reason why a developed economy would escape the vagaries of the weather due to avoidance of sectors that depend excessively on the climate. More so less developed countries would have less incentive to innovate owing to the costs associated with frontier innovations. Inevitably, this magnifies the opportunity cost of bootstrapping out of poverty and entrench the tendency to feed off the climate sensitive sector with ramifications for further deterioration and reduced growth. Further, information bottlenecks, insecure tenure rights and lack of inputs may set an upper bound on the ability to migrate out of the climate sensitive sector. The whole process is thus self-enforcing, with less development feeding into high dependence on climate sensitive sectors which in turns results in reduced abilities to undertake frontier innovations to curtail the effects of deteriorating climate. A clear policy option to stave off dependence on the climate sector should include, among others institutional support for developing countries, and reform of land tenure systems and information and credit constraints which militate against the development of frontier technologies in developing countries.

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