Growth, Distribution, and Clean Technical Change*

Guilherme de Oliveira
Department of Economics and International Relations
Federal University of Santa Catarina, Brazil.
oliveira.guilherme@ufsc.br

Abstract

The paper presents a model of economic growth and income distribution, which describes a possible transitional dynamics to clean technical change. The model integrates an innovative behavioral foundation based on evolutionary game theory with a classical-Marxian description of the macroeconomy. For reasonable parameters values, the model shows that heterogeneity among the frequency distribution of adoption strategies on clean and dirty techniques may be a persistent outcome, either in response to pecuniary externality effects or carbon tax policy. It is also demonstrated that an outcome in which all, or at least a great proportion of firms adopt the clean technique is theoretically possible, but inevitably, such a result is only achieved with an initial profitability-reducing shock on income distribution, and thus a downturn on economic growth.

Keywords: Clean technical change; Economic growth; Income distribution; Evolutionary dynamics.

Resumo

O presente artigo apresenta um modelo de crescimento econômico e distribuição de renda, que descreve uma possível dinâmica de transição para mudança técnica limpa. O modelo integra uma fundação comportamental inovativa baseada na teoria dos jogos evolucionários com uma descrição Clássico-Marxiana da macroeconomia. Para valores razoáveis dos parâmetros, o modelo mostra que a heterogeneidade entre a distribuição de frequência da adoção de estratégias com tecnologia limpa e suja pode ser um resultado persistente, seja em resposta ao efeito de externalidades pecuniárias ou uma politica de imposto sobre carbono. Também é demonstrado que um resultado em que todas, ou grande parte das firmas adotam a tecnologia limpa é teoricamente possível, mas inevitavelmente, tal resultado só é alcançado com um choque redutor de lucratividade inicial na distribuição de renda, e assim uma redução do crescimento econômico.

Palavras–chave: Mudança técnica limpa; Crescimento econômico; Distribuição de renda; Dinâmica evolucionária.

JEL code: C73; O44; Q55.

*I wish to thank Gilberto Tadeu Lima, Adalmir Marquetti, Fernando Rugitsky, and Thiago Fonseca for they helpful comments on early versions of this paper. The usual disclaimer applies.

Área: Macroeconomia.

1 Introduction

The world of the twenty-first century has much higher average living standards than any previous period in history. Undoubtedly, a great part of this progress is due to the process of economic growth. The same growth, however, creates perhaps the greatest challenge in our society: anthropogenic climate change. Normally, economists tend to be relatively optimistic about the economic consequences of climate change on the basis that innovation may switch from dirty to clean technologies in response to changes in relative prices in a process of induced technical change.[1]

Standard approaches to this issue are based on the assumption that there is always a backstop technology available that can potentially resolve all environmental problems created by economic activity. Despite that most backstop technologies are not yet profitable, the concept predicts that they will become affordable as a result of the natural resources depletion or sink. The idea goes back to Nordhaus (1973) and is influential in most economic models and discussions of climate change (see, e.g., Nordhaus 1994; Nordhaus and Boyer 2000; Nordhaus 2008).[2] Along with other factors, the concept suggests that we can (and, indeed, we should) face the problem of climate change with moderate policies, only slowly reducing the pace of greenhouse gas (GHG) emission in the present.[3]

When the choice of technique is not modeled, this exogenous treatment for technical change has an unsatisfactory answer for the climate change challenge. Even from a theoretical perspective, it seems illusory to believe that changes in the relative prices of dirty and backstop technology can account for the whole history. In fact, recently, the issue has received a more complete treatment from part of the endogenous growth literature (Acemoglu et al. 2012, Aghion et al. 2016 and Acemoglu et al. 2016). This literature has important insights about the process of inventing new techniques. However, some questions concerning the process of technology adoption, mostly in line with robust empirical evidence, remain open.[4]

First, standard models routinely treat the innovation process by assuming atomistic agents, in which the answer of why an individual firm does or does not adopt clean technology is obtained from the solution of an inter–temporal maximization problem, which ignores strategic decision aspects. Important as the maximum orientation of the firm may be, my argument here is relatively

[1]Some ecological economists, on the other hand, advocate that only a de-growth strategy, or at least a steady-state economy, can resolve this and other challenges, see, for example, Daly (1991) and Kallis et al. (2012). For a model of induced environment-saving technical change along classical lines, see Foley (2003).

[2]Michl and Foley (2007), for instance, developed a classical–Marxian model that analyzes the growth and distribution effects of the so-called Hubbert's peak (the end of a petroleum-based technology). In the model, portfolio effects on oil property express themselves in changes in income distribution and capital accumulation, thus affecting and being affected by the transition from dirty to clean technology.

[3]This is sometimes called the climate–policy ramp. Stern (2007), meanwhile, calls for a quick rise in political action.

[4]In the heterodox tradition, the process of clean technical change has receiving little attention. See Foley (2003) for a notable exception.

different: the existence of strategic interaction and *coordination failures* may prevent firms from switching from dirty to clean technology, even under the occurrence of increasing returns to the adoption of the latter. In this context, these failures assume a particular form: the cost of adoption is decreasing in the number of firms taking the same action, but potential positive outcomes are not taken into account in the individual decision process. As a consequence, an environmentally inferior equilibrium in which no firm uses clean technology may emerge. To paraphrase Myrdal (1957), the technology adoption dynamics can also be understood as a process of *cumulative causation*.

A second issue is whether the design of correct incentives (a carbon tax, for instance, even in a context of a tough policy action) can account for a "sufficient" rate of adoption necessary to "resolve" the climate change problem. This brings us back to a problem that classical economists have refer to as "getting the rules right".[5] The criticism would be simply that it is not obvious that such a design produces an aggregate outcome in which all, or at least a great fraction, of firms will adopt the environment-saving technique in the long run. A strictly empirical feature of the innovation process is the coexistence of different production techniques in a competitive environment (Arthur, 2011). Whether this feature also holds true for the clean technology, and how the persistence of these heterogeneous strategies may determine (and be determined by) growth, distribution, and climate change outcomes, are still, in my view, relevant open questions.

A first step in addressing these issues is to elaborate a model in which the heterogeneity and adaptive strategic behavior of firms is explicitly accounted for in the process of technical choice. The main purpose of this paper is to develop such a model, in which I ask the following questions: In large populations of firms, what accounts for the diffusion and maybe the non-use of the available clean techniques? What are the growth and distributional effects along the corresponding transitional dynamics?

The model proposes a novel behavioral foundation for the process of technical choice in which heterogeneous firms interact through the so-called *replicator dynamics*. The focus on the microeconomic dimensions is primarily to understand macrodynamics so that the behavior of individual firms co-evolves with a classical-Marxian description of the macroeconomy. The political economy of classical economists has important insights for understanding technical choice. Marx himself was quite concerned with the role of innovations in the determination of profits, as well as with the possibility of *coexistence* among different modes of production, affecting the accumulation dynamics in the capitalist sector. In this context, this paper treats clean technology partially along the lines of Michl and Foley (2007); however, its novel behavioral foundation brings new contributions to the field.

The remainder of this paper is organized as follows: Section 2 presents the structure of the model, followed by the description of its behavioral foundation in Section 3. In Section 4, the macrodynamics effects are analyzed in detail. The paper closes with some final remarks.

[5] See Bowles (2004).

2 The model

Consider an economy with two classes: workers and capitalists. Only one good, X, is produced, and it can be either consumed or invested. The production process is carried out by a fixed (and large) number of firms that are homogeneous except regarding their production techniques, which results in different cost structures. At any moment in time, X can be produced by a fraction, $p \in [0,1]$, of firms applying capital and labor alone in fixed proportions using a "clean" technique that does not pollute. Alternately, it can be obtained by the remaining fraction of firms, $1-p$, using a "dirty" technique responsible for all negative externalities on the environment.[6]

Firms produce using homogeneous capital stock, K (for simplicity, assumed to be non-depreciating), and homogeneous labor, L. As the capital stock is homogeneous, it is supposed, without any loss of generality, the clean technique is a more sustainable technique of production. This simply means that the clean firm, c, uses the existing capital stock in a less polluting way than the dirty firm, d. To focus on the adoption of clean technology, I abstract from other sources of technical change, in particular, labor–saving technical change.

The dirty technique dominates the clean technique, meaning that its labor productivity, x_d, and output–capital ratio, ρ_d, are greater than that of the clean technology, x_c and ρ_c. With capital stock homogeneity, it is supposed that the capital–labor ratio is identical across both techniques; thus $k_d = k_c$. As in Michl and Foley (2007), this brings the convenience of imposing a Hicks-neutral pattern of the technical progress driving growth and distribution.

The clean firm pays workers a wage, w_c, a cost to adopt and use the clean technology, τ_c, and it retain the residual as profits. Such a cost of adoption and use is over the capital stock of c-firms, for simplicity. The total profits *per* unit of capital measure the profit rate, r_c. The dirty firm pays workers a wage w_d the cost for the use of dirty technology, τ_d, which can be either its intrinsic (fixed) value or a carbon tax, the latter defined over the flow of GHG emissions. All residual is retained as cash flow, which defines the profit rate of d-firm, r_d. At any moment in time, both costs are given; in the next section, I describe its behavior in detail. Therefore, it is possible to write the *wage–profit* for the c-firm and d-firm, respectively, as follows:

$$w_c = x_c[1 - \frac{(r_c + \tau_c)}{\rho_c}], \tag{1}$$

$$w_d = x_d[1 - \frac{(r_d + \tau_d)}{\rho_d}]. \tag{2}$$

The wage–profit relation for both firms says that there is a tradeoff between wages, profits, and the cost of each technique given the value of output. The conventional wage is fixed and equal in both firms so that it is the difference regarding the cost structure that will affect the distribution of profits in each type of firm (as detailed in the Section 2.1).

Regarding the uses of output, X, it is supposed that workers as a class spend all of their

[6] As I suppose that there is one backstop and one dirty technique available to all firms, I can use the terms clean and dirty technology, respectively. From this point on, I refer to clean firms and dirty firms as c-firm and d-firm, respectively.

wages, whereas capitalists save a common fraction, s, of their aggregate profits and use them for investment purposes. Therefore, ω_c and ω_d can be defined as the consumption *per* worker (including the capitalist's consumption), and g_{k_c}, g_{k_d} the growth rate of capital stock of both clean and dirty firms, respectively. Thus, the counterpart of the wage–profit relation is the following *consumption–growth* relation:

$$\omega_c = x_c(1 - \frac{g_{k_c}}{\rho_c}), \tag{3}$$

$$\omega_d = x_d(1 - \frac{g_{k_d}}{\rho_d}). \tag{4}$$

Note that the consumption–growth schedule in both firms is instantaneously unaffected by changes in the distribution of income; therefore, it is identical to the wage–profit schedule only when the cost of clean and dirty technology are both equal to zero.

The aggregate behavior of the economy depends on the fraction of firms using clean and dirty technologies, p and $1-p$. Hence, we can re-write (1) and (2) as (3) and (4) to express this aggregate behavior as follows:

$$\bar{w} = px_c[1 - \frac{(r_c + \tau_c)}{\rho_c}] + (1-p)x_d[1 - \frac{(r_d + \tau_d)}{\rho_c}], \tag{5}$$

$$\bar{\omega} = px_c(1 - \frac{g_{k_c}}{\rho_c}) + (1-p)x_d(1 - \frac{g_{k_d}}{\rho_d}), \tag{6}$$

which represents the *average growth and distribution schedule* in Figure 1.

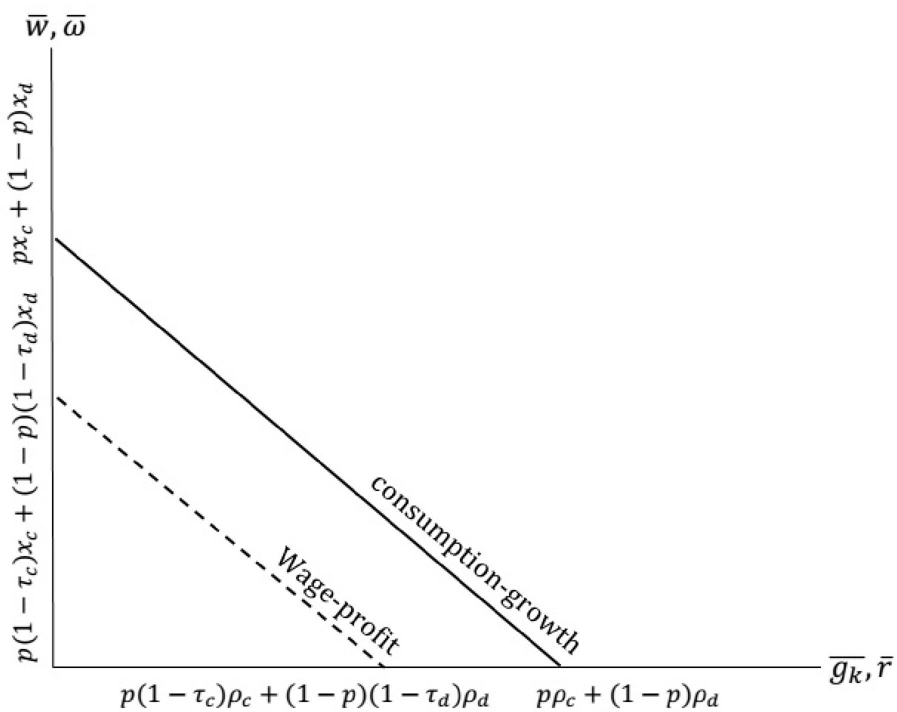

Figure 1: The average growth and distribution schedule.

The average consumption–growth relation shows the pair of g_k and ω that describes the composition of output between investment and consumption. The heterogeneity changes the interpretation of the average aggregate results. Now, the average growth changes with the productivity differential of x and ρ and with the proportion of firms adopting clean or dirty technology, p and $1-p$, respectively.

When the proportion of firms using clean technology rises, with capital and labor productivity remaining constant, the consumption–growth relation lowers, $\partial\bar{\omega}/\partial p < 0$, in a Hicks-neutral sense that lowers economic growth. This is only true if the profitability of the clean innovation is less than the profitability of the dirty innovation (whose adjustment is via cost, as detailed below). Regarding distributional effects, note that they depend on the cost structure of both techniques. Suppose that, just as a first approximation, that these costs are fixed and equal. Thus, a rise in the fraction of firms using clean technology will have a negative effect on the average wage–profit schedule, with this frontier decreasing because the dirty technique dominates the clean technique, $\partial\bar{w}/\partial p < 0$.

2.1 The behavioral foundation

This paper covers some of the same ground as Foley and Michl (1999), but it differs regarding the behavioral foundation of capitalists. First, it avoids complications of optimal control to describe the savings behavior of capitalists; thus, it is more closely related to the formulation of Marglin (1984) and Dutt (1990) for the classical–Marxian model, just supposing that capitalists save a constant fraction of their profits. In the present instance, forward-looking behavior of capitalists is not the whole picture. Capitalists are inserted in a competitive environment in which the decision process is taken on the basis of a *historical learning*, which is locally acquired.

At any moment in time, a proportion, $\alpha \in [0,1]$, of both c- and d-firms in this market consider the possibility of switching their production technique. The remaining firms do not contemplate such a possibility irrespective of their past experience. This feature captures the fact that not all firms are open to change at each moment in time. They typically keep choices either in clean or dirty technology over a period of time. α can be subject to historical learning, but I simplify matters by assuming that it is exogenously given. The size of this parameter will account for the speed of adjustment of the transitional dynamics.

Firms are randomly matched. This can be seen as an exchange in the market, but it is not necessarily a geographical matching. Thus, at any period, the expected number of c-firms seeking to switch to dirty technology who are matched with d-firms is $\alpha p(1-p)$. Each potential adopter firm meets just one firm *per* period, either changing its technique or not. The probability of a technique switch depends on the evaluation of the difference between the profit rate of both techniques, whose expressions are obtained from (1) and (2) as follows:

$$r_c = \frac{x_c - w_c}{k} - \tau_c, \tag{7}$$

$$r_d = \frac{x_d - w_d}{k} - \tau_d. \tag{8}$$

Firms use a learning-based rule: if a d-firm considering adopting the clean technique meets a c-firm, the switch occurs if the profit rate of the dirty-based technology is smaller than the profit rate of the clean-based technology. A small difference in profit rates need not induce the change; thus, with probability, $\beta(r_c - r_d)$, the d-firm will innovate if $r_c > r_d$. If $r_c \leq r_d$, the firm will not adopt the clean technique. β is a positive parameter reflecting the effect on switching of relatively large profit rates differences, but it is exogenously given and sufficiently small to ensure that such probability varies over the unity interval.

Taking the expected values of a large population of firms, it is possible to write the expected population frequency adopting the clean technique in time $t+1$, p_{t+1}, as:

$$p_{t+1} = p - \alpha p(1-p)\lambda_c \beta(r_d - r_c) + \alpha p(1-p)(1-\lambda_d)\beta(r_c - r_d), \tag{9}$$

where $\lambda_c = 1$ if $r_c > r_d$ and zero otherwise, and $\lambda_d = 1$ if $r_d > r_c$, and zero otherwise. Therefore, the expected number of clean firms in the next period is the proportion of c-firms in this period, minus any c-firm that switches from clean to dirty technology, plus any dirty firm that switches to the clean technique. Under $\lambda_c + \lambda_d = 1$, we can rearrange this equation taking its time derivative in the following manner:

$$\frac{dp}{dt} = \alpha p(1-p)\beta(r_c - r_d), \tag{10}$$

which is the so-called *replicator dynamic equation*, from which it can be seen that the direction and pace of the adoption of clean technology depend on the value of p, the profit rate differential, and the number of potential adopter firms.[7]

Note that the variance of profit rate, $p(1-p)$, measures the number of c-firms that will be paired with a d-firm. The extreme values of p make this matching very unlikely. Supposing that costs are exogenously given in (7) and (8), it is readily seen that the two unique values of p that stabilize (9) are 0 and 1. Thus, if $r_d > r_c$, the equilibrium $p = 0$ is an attractor, and no firm will eventually adopt clean technology. However, if $r_c > r_d$, $p = 0$ is a reppeler and all firms will eventually adopt clean technology. Of course, such a simplified analysis is very unsatisfactory, and we need the support of a theory or some empirical evidence to describe the cost structure of each technique.

It is reasonable to suppose that, on average, a clean technique is more costly than its average dirty substitute. In fact, there are many policy debates on how to invert, or at least reduce, this inequality (see Acemoglu et al. 2016).[8] Most propositions focus on the design of a carbon tax over dirty techniques or on the design of a cap and trade system. The idea is to create a mechanism to raise the dirty technique share in the total cost in order do induce the adoption (and even the invention) of clean techniques. Both mechanisms have been attracting the attention of a substantial

[7]See for example, Gintis (2009) for details about the mathematical derivation and properties of the replicator dynamic equation.

[8]A recent international round of negotiation was the Sustainable Innovation Forum ($SFI15$) held in Paris 2015, where 90 have discussed a climate agreement with ambitious emission abatement targets.

number of researchers, and the body of literature on the topic is growing.

Aghion et al. (2016), using patents data on dirty and clean technologies in the American automobile industry from 1978 to 2007, find a sizable impact of carbon taxes on the direction of innovation. They also show that the share of clean over dirty patents has experienced a steady increase since 1990. In 2007, for instance, around 4 clean patents were filed for every 10 dirty patent. They also provide evidence that clean innovation has a self-perpetuating nature feeding on its past success. Concretely, firms with past experience in dirty patenting are more likely to pursue dirty innovation activities in the future. The reverse is true for firms that have been more active in clean patenting. This result is striking since it suggests that heterogeneity may be persistent, a result that can emerge in the model set forth in this essay.

The authors do not present statistics of emissions in the sector. Even so, it is not clear how much of the reduction on the pace of emission in this sector is due to innovation or command and control policies. This question was investigated in India by Harrison et al. (2015), whose paper compares the impacts of environmental regulations with changes in coal prices on establishment-level pollution abatement, coal consumption, and productivity. They find that higher coal prices reduce coal use within establishments and are associated with lower pollution emissions at the district level.

In turn, Bruvoll and Larsen (2004) investigate the effectiveness of carbon taxes in reducing GHG emissions in Norway. For this particular case, despite considerable tax increases for some fuel types, the effect has been modest. They show that while the partial effect from lower energy intensity and energy mix changes was a reduction in $CO2$ emissions of 14 percent, the carbon taxes contributed to only a 2 percent reduction. Therefore, the evidence on the effectiveness of carbon taxes is mixed and expectedly heterogeneous among countries. Even if one believes that the effect is positive, concretely, not much is known about the size of the impact in the long run.

Inspired by this evidence, the present paper explores two distinct settings. First, it models the feature that a clean technology has a cost threshold, from which the adoption becomes profitable for firms. The cost threshold is determined by the point at which the profit rates of clean and dirty firms are equalized. In turn, the cost of adopting clean technology is decreasing within the firms adopting it. This effect is represented by a linear function that is defined as being equal to the following:[9]

$$\tau_c = \gamma_o - \gamma_1 p, \tag{11}$$

in which γ_0 represents the intrinsic cost of the clean technique in the absence of strategic complementarity among firms and γ_1 is the cost sensitivity to changes in the proportion of firms producing with the clean technique, representing a pecuniary externality effect or the internal economies of scale. The cost of the dirty technique remains exogenously determined and constant over time, thus reflecting a scenario in which the cost of a dirty-based technology takes some time to respond

[9]There is no substantial gain in using a nonlinear specification.

to changes in the stock reserves, for instance. I will call this setting of the *non-regulated regime*. In this game, we can use (11) in (7), and treat τ_d as parametric in (8).

The pecuniary externality effect arises when the interdependence of firms takes place through the market mechanism (Scitovsky, 1954). In the present instance, the production of the clean technique is exogenously given, but the cost of production is supposed to be a decreasing function of the extension of the market for clean technology. Therefore, when a firm chooses to produce with the clean technique, it enlarges the market for clean technology, thus positively affecting profits of other firms in the market that can benefit from a lower cost of adoption. This strategic complementarity illustrates the occurrence of increasing returns to scale or cumulative causation effects in the adoption process.

However, an environmental policy may exert an important role in the process of technical choice. In exploring this possibility of intervention in the non-interventionist game, a second setting supposes that an environmental authority designs carbon taxes that are applied to GHG emissions, the *regulated regime*. To model this, suppose that the flow of emissions, G, is determined by a composition output effect under the assumption that only d-firms generate negative externalities on the environment in a non-negligible amount: so that:

$$G = (1 - p)X, \tag{12}$$

in which the flow of GHG emissions is related with the flow–stock production equation.

The tax rate, μ, is applied to G so that $\tau_d = \mu G$ is the tax revenue, representing for firms the new aggregate cost of adopting the dirty technique. It is further supposed that all of the corresponding tax revenue is used in the recovery of the environmental quality, ϵ, whose efficiency in the recovery of the environmental damage is measured by the exogenous parameter, $0 < \phi < 1$. The higher the ϕ, the higher the efficiency of the abatement activity.

The environmental quality grows according to a logistic function, $L = \chi(E - \epsilon)\epsilon$, the perhaps easiest way to model the environmental dynamics. χ is the intrinsic growth rate of environmental quality and E is the maximum carrying capacity point, from which, in the absence of anthropogenic influences, further growth cannot occur, $L = 0$.

In addition, the flow of GHG emission negatively affects the level of environmental quality, whose marginal impact is normalized to one for the sake of simplicity. Therefore, the rate of change of the environmental quality is equal to $\dot{\epsilon} = L - (1 - \phi\mu)G\epsilon$. The proportional rate of change of environmental quality, thus, is defined as follows:

$$\hat{\epsilon} = \chi(E - \epsilon) - (1 - \phi\mu)(1 - p)X, \tag{13}$$

where $\hat{\epsilon}$ denotes $\dot{\epsilon} \equiv d\epsilon/dt/\epsilon$.

In the regulated regime, we can use (11) in (7), but now, (8) is replaced by the following equation:

$$r_d = \frac{x_d - w_d - \tau_d}{k}. \tag{14}$$

The reason is that now, the cost of the dirty technique is measured as a flow, which depends on the GHG emissions in a similar way as labor in the d-firms' technology.

Inserting both cost descriptions, τ_c and τ_d, in the profit rate function of each type of firm, (7), (8), and (14), we can compute the new stability properties of the replicator dynamics as well as its effects on income distribution and capital accumulation in the long run. The next section explores these transitional dynamics in the context of a Classical–Marxian model of economic growth.

A comment as regards this novel behavioral foundation, however, is in order. Microeconomic models using evolutionary game theory have been successfully adopted by Bowles (2004) in a series of works. Silveira and Lima (2016), in turn, have extended this application to understand the co-evolution between microeconomic motives and macroeconomic outcomes. The authors measure the impacts of effort elicitation over income distribution and economic growth in a post-Keynesian growth model.[10] The present paper draws a great deal of inspiration from these previous theoretical initiatives.

3 The classical–Marxian closure

At any moment in time, the profit rate, the real wage, the cost of adopting clean technology, the flow of emissions, and the carbon tax are all given. The economy moves over time due to changes in the proportion of firms using clean technology, capital accumulation, and the level of environmental quality.

The conventional wage is exogenously determined by the material goods required to sustain workers and their families in both kinds of firms. Along with the proportion of firms using clean technology, obtained from the equilibrium solution of the replicator dynamic equation, (10), with wages as exogenous, the profit rate is determined. As mentioned before, both types of capitalists save a fraction, s, of their profits, and as there are no effective demand complications, savings ($S \equiv I$) determines the pace of capital accumulation according to the following function:

$$g = s\bar{r} = s[pr_c + (1-p)r_d], \tag{15}$$

in which there is no depreciation rate and $\bar{r}$ is the average profit rate. Note that the intensity of capital accumulation changes with the proportion of firms using dirty or clean technology. In turn, the capital stock of d-firms will solve for GHG emission in (12), which jointly with p determines the level of environmental quality in the economy.

Therefore, the causality channel in this Classical–Marxian model remains loyal to its steady-state representation, as in Marglin (1984), but it is made dependent on the historical learning of firms. The important aspect is that in equilibrium, the model is able to generate the classical profit rates equalization through evolutionary dynamics. Given its novel behavioral foundation, I refer to

[10]This research program, however, is not new. See, for example, Silveira and Lima (2008) for an early macrodynamic model with evolutionary dynamics.

the model as evolutionary.[11]

3.1 The non-regulated regime

In the non-regulated regime, we use (11) and (7) into (10) to determine the new replicator dynamic equation:

$$\frac{dp}{dt} = \alpha p(1-p)\beta[r_c(p) - r_d], \tag{16}$$

in which r_c is a function of p.

Initially, we see that this equation has two corner solutions: $p^* = 0$ and $p^* = 1$. Computing the partial derivative, $\partial \dot{p}/\partial p$, (where $\dot{p}$ indicates the time derivative) at the equilibrium values, respectively we have the following:

$$\left.\frac{\partial \dot{p}}{\partial p}\right|_{(p^*=0)} = \alpha\beta(\rho_c - \rho_d + \tau_d - \gamma_0), \tag{17}$$

$$\left.\frac{\partial \dot{p}}{\partial p}\right|_{(p^*=1)} = (\alpha\beta - 2\alpha\beta)[\gamma_1 + (\rho_c - \rho_d + \tau_d - \gamma_0)]. \tag{18}$$

Recall that dirty technology dominates clean technology, $\rho_d > \rho_c$, but suppose that this capital productivity differential is not too high. In this case, the stability condition for the equilibrium in which all firms are using dirty technologies, $p^* = 0$, requires that the cost of the clean technology in the absence of pecuniary externality or strategic complementarity effect, γ_1, be relatively high so that $\|\gamma_0\| > \tau_d$. In practice, as discussed earlier, the intrinsic initial cost of an average clean technology is likely be to relatively higher than the cost of its dirty substitute. Therefore, in the non-regulated regime, this condition is usually satisfied.

As the stability of $p^* = 0$ is supposed to usually hold, the equilibrium in which all firms switch to clean technology, $p = 1$, is locally asymptotically stable only when the magnitude of the pecuniary externality effect over the new technique, γ_1, is relatively strong enough (18). Meanwhile, if the magnitude of the pecuniary externality is relatively weak, the equilibrium with $p^* = 1$ is locally unstable.

If stability is the normal state of affairs, then, there is an interior solution for p^*, which satisfies $r_c(p) - r_d = 0$, it is equal to the following:

$$p^* = \frac{\rho_d - \rho_c + \gamma_0 - \tau_D}{\gamma_1}, \tag{19}$$

which is always in the interval $[0, 1]$ when the pure strategy equilibrium, $p^* = 1$, is locally stable; thus $\gamma_1 > (\rho_d - \rho_c + \gamma_0 - \tau_D)$.

Figure 2 plots the transitional dynamics in the non-regulated regime. Panel (b) shows the result for the solution with only a corner equilibrium, in which the profit rate of the dirty technique is

[11] See Duménil and Levy (1995) for a classical–Marxian evolutionary model of endogenous technical change.

always above the profit rate of its clean substitute given a relatively weak pecuniary externality effect, γ_1. The economy is experiencing the positive feedback in the adoption of dirty technology. In this case, $p^* = 1$ is locally unstable and $p^* = 0$ is locally stable, and it is only by a fluke that firms will promote the environmental benefits of a complete transition to clean technology.

Panel (a) shows the setting with an interior solution. The straight line is the profit rate of d-firms that is independent of p. In turn, r_c is positively sloped, as in panel (b), but now, the pecuniary externality effect is relatively strong enough to produce an interior solution for p. To the left of p^*, firms are under the influence of the positive feedback in the adoption of dirty technology. However, to the right of the mixed-strategy equilibrium, the positive feedback is now influencing the clean technology. It can also be stressed that despite the existence of this unstable equilibrium, it is very unlikely (mathematically impossible) that it it can be achieved. It is only through an exogenous exact shock, or if the economy begins exactly at that equilibrium, that p^* is achieved.

However, we can compute the impact of a change in the exogenous parameters on the mixed-strategy equilibrium value of the distribution of adoption strategies. From (19), note that p is increasing in the magnitude of the capital productivity differential, $\rho_d > \rho_c$, as well as in a relatively high intrinsic cost of adoption of the clean technique, γ_0. Of course, as the equilibrium is asymptotically unstable, these results disfavor the adoption of the clean technique, increasing the region of negative cumulative causation to the left of p^*, in which coordination failure prevails. The coordination failure assumes the form of a non-cooperative behavior since, because of the relatively high instability, potential firms cannot plan a collective action.

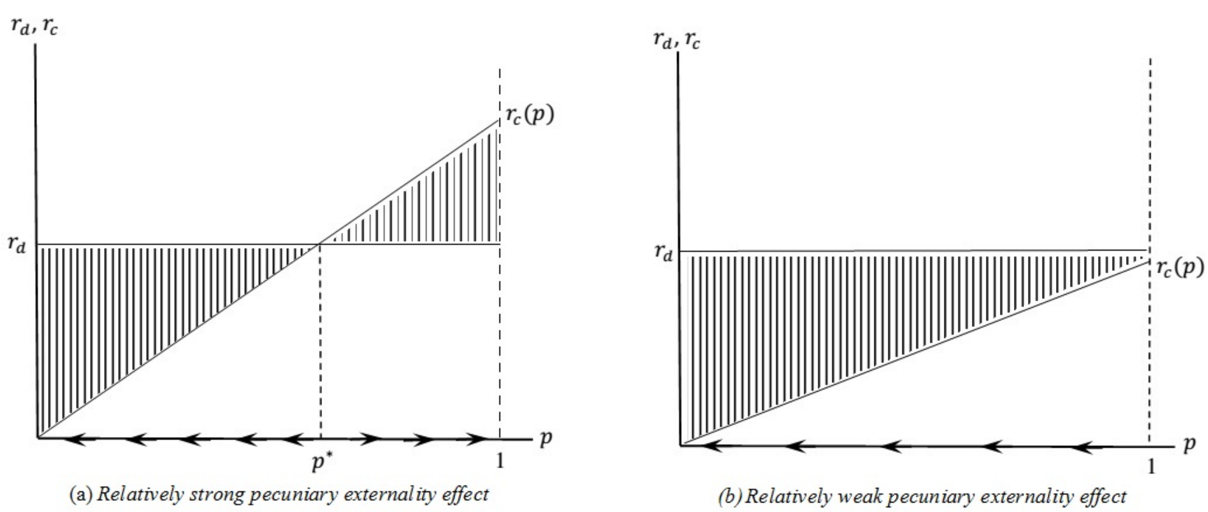

Figure 2: Transitional dynamics in the non-regulated regime.

In turn, the partial derivative, $\partial p/\partial \gamma_1 < 0$, implies that the mixed-strategy equilibrium of the distribution of techniques, which also represents the cost threshold (the point where $r_c = r_d$), is decreasing in the extension of the pecuniary externality effect over the clean technique, γ_1. The same result is true for the cost of the dirty technique since an increase in τ_d reduces the profit rate of d-firms.

The non-regulated regime has implications for income distribution and economic growth. From the definition of average profit rate, $\bar{r} = pr_c + (1-p)r_d$, we have the following solution for the profit rate in the corner equilibrium values:

$$r(p^*) \equiv r(0) = \left(\frac{x_d - w_d}{k} - \tau_d \right), \tag{20}$$

$$r(p^*) \equiv r(1) = \left(\frac{x_c - w_c}{k} - \gamma_0 + \gamma_1 \right). \tag{21}$$

As in the absence of any depreciation rate, the capital accumulation function is simply $g = s\bar{r}$; it is straightforward to obtain the capital accumulation values in each equilibrium point from (20) and (21). Figure 3 plots the profit rate and the capital accumulation function for both relatively weak (panel a) and strong (panel b) pecuniary externality effects. Of course, in both cases, the capital accumulation is a mirror of the profit rate and the levels difference are given by the saving rate, s. The slope's differential tend to reduce as both curves approach the mixed-strategy equilibrium (the point of equalization of profit rates).

Note in panel (a) of Figure 3 that all along the p-axis, the dirty technology is in a region of positive cumulative causation. As in this case, $r_d > r_c$, the profit rate and capital accumulation are monotonically increasing toward $p^* = 0$ in an environmentally inferior equilibrium. Meanwhile, if by a fluke, the economy is in the equilibrium point, $p^* = 1$, both growth and distribution are lower than in the complementary subset of the economically relevant domain.

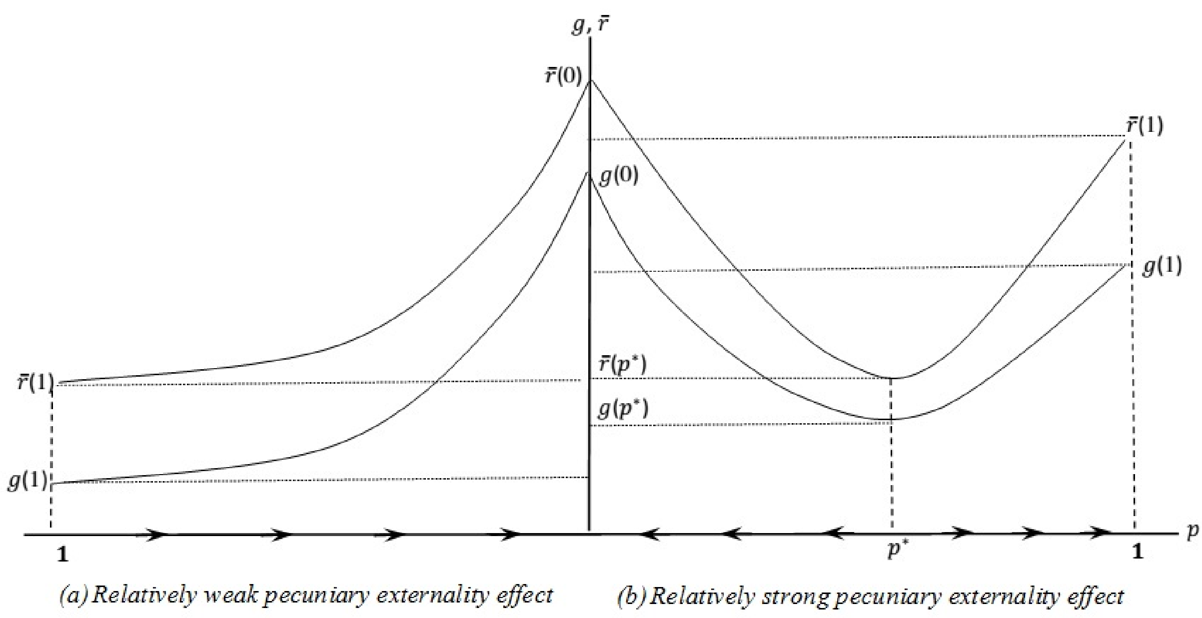

Figure 3: Growth and distributional effects in the non-regulated regime.

In panel (b), the dynamics of growth and distribution are nonlinear. If the economy is at the interior equilibrium point, p^*, the average profit rate is at its lowest possible value. The lower profit rate also results in a slower pace of capital accumulation. However, as previously mentioned before, it is very unlikely that p^* will be achieved. To the left of the mixed-strategy equilibrium of the frequency distribution of techniques, the dirty dominates the clean technique, monotonically increasing profits and capital accumulation.

To the right of p^*, as the the profit rate of the c-firm is greater than that of the d-firm, the average profit rate is increasing, positively affecting the pace of capital accumulation. Whether the new pace of economic growth and level of income distribution will return to the previous pattern of dirty technology, $g(0)$ and $r(0)$ for example, depends on the distribution of adoption strategies and the intensity of the internal effect on clean technology. The higher the internal effect, the lower the adoption cost threshold and the more sloped is the profit rate of c-firm in Figure 3; thus, this is more likely the achievement, or overcoming, of the previous pattern of income distribution and economic growth, even if possibly slowly.

3.2 The regulated regime

Suppose that the government knows the main results of the non-regulated regime illustrated in the previous game and decides to intervene in the process of choice of technique through its carbon taxes mechanism. Using the tax rate, μ, substituting (11), (7), and (14) into (10), the new replicator dynamic equation becomes the following:

$$\frac{dp}{dt} = \alpha p(1-p)\beta[r_c(p) - r_d(p)], \tag{22}$$

where now both profit rates depend on p.

It is readily seen that this equation has two corner solutions whose partial derivatives with respect to p are equal to the following:

$$\left.\frac{\partial \dot{p}}{\partial p}\right|_{(p^*=0)} = \alpha\beta[\rho_c - \rho_d - \gamma_0 + \mu\rho_d^g], \tag{23}$$

$$\left.\frac{\partial \dot{p}}{\partial p}\right|_{(p^*=1)} = (\alpha\beta - 2\alpha\beta)[\gamma_1 + (\rho_c - \rho_d - \gamma_0)], \tag{24}$$

where ρ_d^g is given by X/K_d, which is different from $\rho_d = X_d/K_d$ outside the corner solution. ρ_d^g indicates how much of the total production is produced by one unit of capital in $d-$firms. The higher the productivity, the lower the level of environmental quality since the scale of production effect is negatively affecting ϵ in (13). In practice, it is the tax revenue that is normalized by the capital stock of the $d-$firm.

The conditions for (in)stability are more complicated. Note that if the intrinsic value of the clean technique, γ_0, is relatively higher than the normalized carbon tax revenue so that $\|\gamma_0\| > \mu\rho_d^g$, the equilibrium point, $p^* = 0$, is locally stable. In this case, the profit rate of c-firms is lower than that of d-firms. On the other hand, if the capital productivity differential is not relatively too high, and if the normalized carbon tax revenue is relatively high so that $\|\mu\rho_d^g\| > \gamma_0 + \rho_d - \rho_c$, it follows that $p^* = 0$ is a local reppeler. In this case, given the wage rate, the carbon tax revenue must be relatively high to produce a negative profit rate for d-firms, which is achieved with relatively high levels of μ. In panel (a), Figure 4 presents the stable solution for $p^* = 0$, while panel (b) shows the unstable case.

If $p^* = 0$ is locally stable, $p^* = 1$ may be asymptotically locally stable if γ_1 is relatively strong enough (panel a) or locally unstable if γ_1 is relatively weak (panel b). If $p^* = 0$ is locally unstable when $\gamma_1 > (\rho_c - \rho_d - \gamma_0)$, it follows that $p^* = 1$ is locally stable. When the pecuniary externality effect is relatively weak, the equilibrium is locally unstable; hence, four cases arise, but only two of them produce a mixed-strategy equilibrium. An interior solution exists if $r_c - r_d = 0$ so that p^*, in both cases, is equal to the following:

$$p^* = \frac{\rho_c - \rho_d - \gamma_0 + \mu \rho_d^g}{\mu \rho_d^g - \gamma_1}, \tag{25}$$

which is always in the interval $[0, 1]$ if the (in)stability conditions are satisfied.

Panel (a) in Figure 4 presents a result similar to the one depicted in Figure 2, panel (a): the stability case. Note, however, that for similar reasonable parameters, the illustration in Figure 4 generates a mixed-strategy equilibrium for the distribution of techniques that is relatively higher than in the previous case. The reason for this is that the relatively weak carbon tax counterbalances the pecuniary externality effect in the denominator of (25). The growth and distributional effects will present a similar pattern, illustrated in Figure 3, panel (b), but in this case, carbon taxes will reduce the level of profits of d-firms, thus lowering the pace of capital accumulation relatively faster.

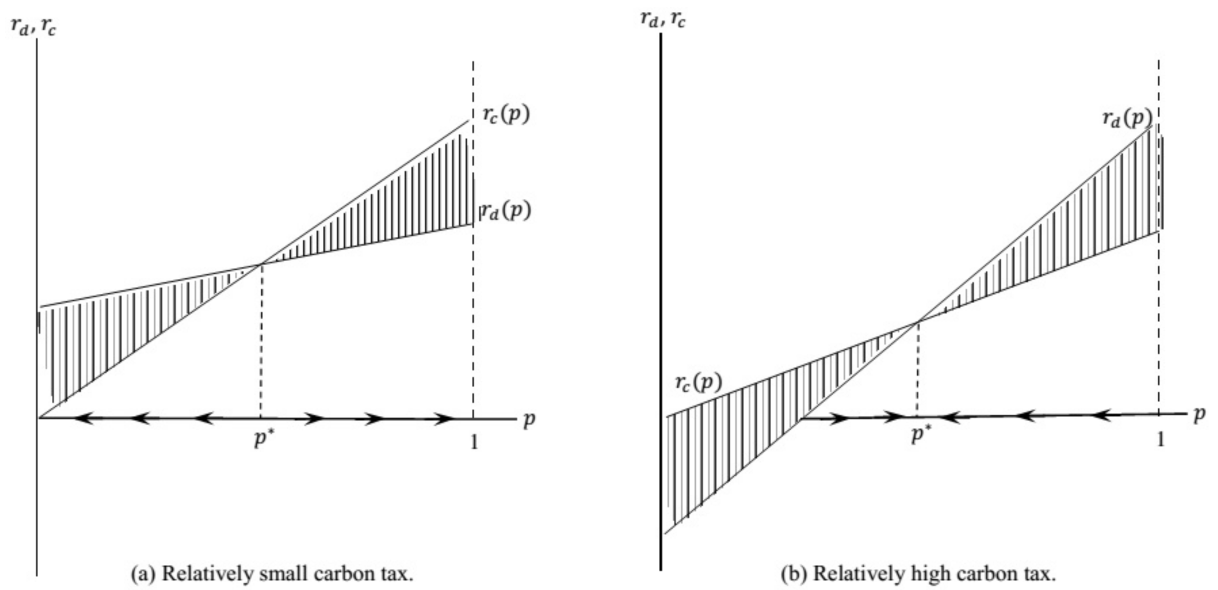

Figure 4: Transitional dynamics in the regulated regime.

Meanwhile, if the gains from the pecuniary externality effect on clean technology are relatively weak, the distribution of adoption strategies will be asymptotically locally stable, with heterogeneity emerging as a persistent feature of the economy. If all firms are using dirty technology, the only mechanism that the government has to confront the effects of positive feedback is to select a carbon tax that, along with the real wage, produces a negative profit rate for d-firms. If a new entrant chooses to produce using the clean technique, it will have a positive profit rate. Now, if a d-firm is randomly paired with the new c-firm, it switches from dirty to clean technology. Thus, all the relevant p domain to the left of the mixed-strategy equilibrium is a region of positive cumulative causation toward the adoption of clean technology.

The economic growth and income distribution are increasing in this region (Figure 5, panel a). Note that both are below zero when the average profit rate is negative. Then, both rates pass through zero before they start to grow at decreasing rates until the equilibrium point, p^*, where both profit rates are positive and equal. At this point, average profits are at their relative maximum level and capital accumulation is at a relatively higher pace.

This macroeconomic outcome is affecting firms' microeconomic behavior. As capital is accumulating in firms using clean technology, the flow of GHG emissions is steadily decreasing toward p^* and the tax revenue is progressively smaller over the total profits of d-firms, which explains why the profit rate of d-firms is also rising. To the right of the mixed-strategy equilibrium, however, a relatively low flow of pollution produces a relatively higher profit rate for dirty firms than for clean firms. As τ_d is falling relatively faster than τ_c, it becomes relatively more profitable to invest in dirty techniques from this point on. Economic growth starts to increase now based on the use of dirty technology.

The political economy consequences of this result are complex. The presence of carbon taxes can induce the adoption of clean technology, which reduces capital accumulation and economic growth in a relatively slow pace in the beginning of the convergence process. In fact, such a result produces negative growth. In addition, if the pecuniary externality effect is relatively weak, in an amount insufficient to cover the correspondent marginal decrease in the dirty share in total cost (as p is increasing), the transitional dynamics induced by the regulated regime produce a *dirty technological trap*.

In this case, the question becomes whether this technological trap is relatively closer to the origin, where most firms are using dirty technology, or closer to the pure equilibrium point, where at which a large fraction of firms are using clean technology. The answer depends on the capital productivity differential, the intrinsic cost of clean technology, the pecuniary externality effect, and the carbon taxes.

If the capital productivity differential is relatively high (but not enough to violate the stability conditions), the mixed-strategy equilibrium frequency distribution of adoption strategies will be closer to the origin. A relatively high intrinsic cost of clean technology in the absence of strategic complementarity produces a result in the same direction. In turn, the pecuniary externality effect and the carbon tax are positively associated with p^*. Note also that in this situation, the mixed-strategy equilibrium is relatively lower than p^* in the non-regulated regime for similar plausible parameters.

As regards the normalized carbon tax revenue, the result is ambiguous. If $p^* = 1$ is unstable, when the pecuniary externality effect is relatively weak, the carbon tax will be higher and thus the mixed-strategy equilibrium will be higher. In the stable case, as the pecuniary externality effect is relatively high, the carbon tax negatively affects the mixed-strategy equilibrium. Of course, in both cases, this result favors the adoption of clean technology.

From the environmental and ecological perspective, the ideal solution is only achieved if the

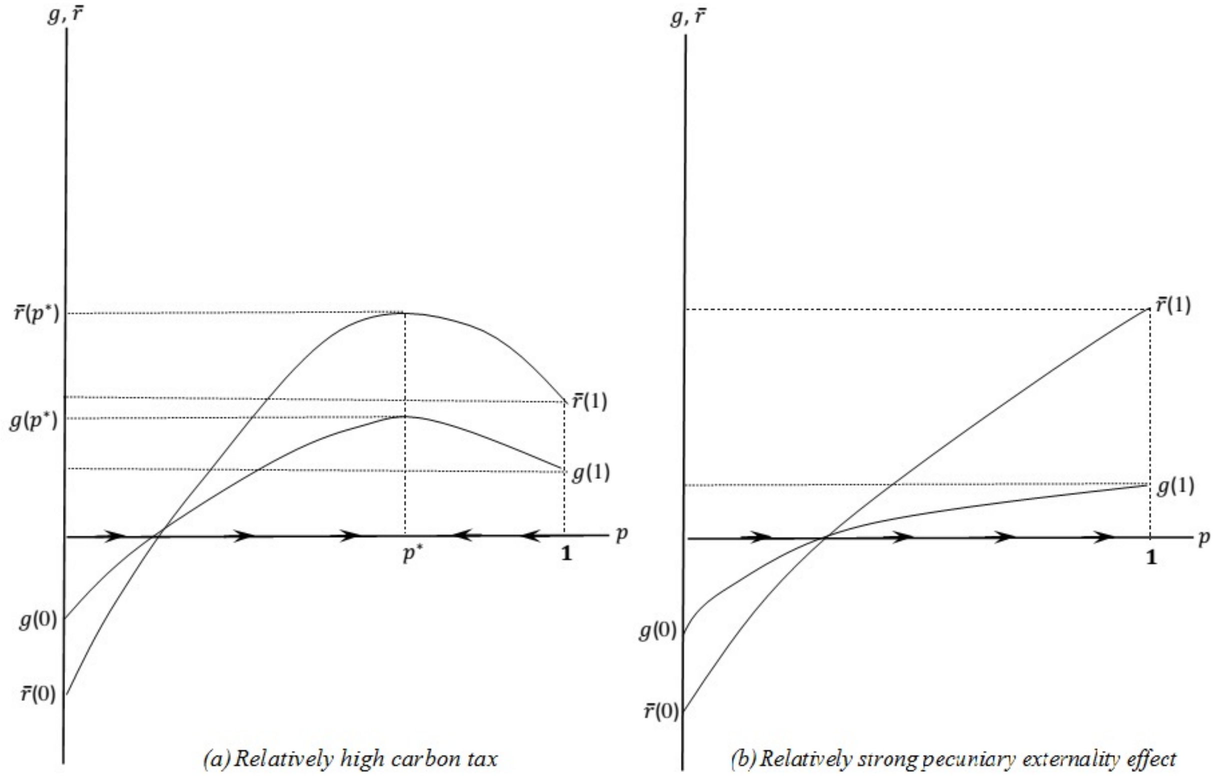

Figure 5: Growth and distributional effects in the regulated regime.

carbon tax is relatively high, producing an unstable equilibrium point when all firms are using the dirty technology ($p^* = 0$), and when the pecuniary externality effect is also relatively strong enough to produce a asymptotically stable equilibrium when all firms are using clean technology ($p^* = 1$). In this case, the profit rate of c-firms is always increasing more quickly than the d-firms, and the economy is in transition to clean technology, even if possibly slowly.

The consequences for economic growth and income distribution of this illustrative case are depicted in Figure 5, panel (b). Initially, the carbon tax causes an economic crisis defined as the propagation of profitability loss and negative growth in the economy. Progressively, as firms adopt clean technology, the total profits begin to increase and the growth becomes positive, both at decreasing rates. The flow of emission will decline to zero and the environmental quality converges to its maximum carrying capacity level.

In the present instance, as mentioned before, the government invests all of the corresponding tax revenue into the recovery of the environmental damage. The government has a restriction to increase the tax rate. This restriction emerges from the negative impact of the environmental policy on economic growth. The higher the tax rate, the lower the pace of capital accumulation in the beginning of convergence. Another possibility arises when the government applies all of the tax revenue to the production of clean technology in the form of a subsidy. In this case, the speed with which the price of clean technology is falling is relatively faster than the case illustrated in (8). In addition, the likelihood is that p^* stabilizes closer to the full specialization in clean technology than in the previous case. As the main qualitative result will be the same, I abstract from formally addressing such a possibility.

4 Conclusions

This paper presents a model that provides a novel behavioral foundation for the transition to clean technology in capitalist economies. The model has many limitations and clearly provides (at best) some elements to understand the adoption of clean technology in a context in which the price of backstop technology is not exogenously given.

The adaptive behavior of firms based on historical learning is central to the story, demonstrating that the persistence of a heterogeneous frequency distribution of adoption strategies may be, in various settings previously explored, the normal state of affairs. All these settings are sensitive to reasonable configurations of the parameters, especially the intrinsic value of clean technology, the intensity with which the cost of clean technology decreases with the proportion of firms adopting it, as well the magnitude of carbon taxes.

In a non-regulated regime, in which the cost of adoption of clean technologies is decreasing in the proportion of firms taking the same action, the model shows that instability characterizes the transitional dynamics in the long run. It is only if the clean technology surpasses some cost threshold that its adoption can benefit from the occurrence of positive feedback. In this context, the pecuniary externality effect, in other words, the strategic complementarity behavior of firms, plays a central role. On the other hand, the economy is constantly pushed toward the the full specialization in dirty technology (the non-use of the clean technique) and a possible environmental collapse in the long run. In this case, an exogenous discontinuous shock on fraction of firms using the clean technique is required. Such an exogenous intervention also can be implemented as a governmental policy.

In a regime with relatively high policy activity, the regulated regime, the possibility of a full and continuous transition to clean technology arises. This outcome is achieved through a relatively high carbon tax and a relatively rapid decrease of the cost of adopting on clean technology due to the operation of pecuniary externality effects, which are both central to the argument. At the same time, however, for reasonable parameters, the model also shows that instead of producing full specialization in clean technology, the carbon taxes may push the economy to a dirty technological trap, which is characterized by a stable mixed-strategy equilibrium point from which the economy, if left to the free play of its structural forces, may never escape. This occurs if the strategic complementarity effect on the cost of clean technology is relatively weak.

The contribution of this paper relates to a large and growing literature on the relationship between economic growth, technical change and the environment. Based on economic models of climate change, this literature has suggested either relatively strong and immediate governmental action at a relatively high cost in the present (Stern, 2007), a more gradualist approach, the climate-policy ramp (Nordhaus, 2008) or only a temporary intervention (Acemoglu et al., 2012). The present contribution, thus, indicates that a relatively high governmental interventions is required either in the form of an exogenous shock on clean technology, or relatively high carbon tax.

In addition, the paper shows that the political issue involves more than just the choice of the "correct" intensity of policy actions. Important as this discussion may be, firms' strategic complementarity behavior is crucial in this setting, because it is through it that the positive cumulative causation effects on clean technology operate. Therefore, we cannot give to the complex mechanisms of technological adoption a simplified treatment in the story. Eventually, the design of mechanisms to promote the technological interaction among firms may be a viable environmental policy in the real world.

In terms of growth and distributional effects, if the behavioral foundation of firms and its interaction with macroeconomic outcomes is taken into account, the unique (continuous) scenario that may promote the full transition to clean technology, or at least for a relatively high proportion of firms, is achieved through initial negative adverse effects on income distribution, and thus, economic growth. Note, however, that it effect is not the same as the one proposed by a degrowth strategy. The degrowth strategy focus has been less on a positive approach of the sustainability problem and more on the social transformation necessary to achieve sustainable development. The particular emphasis has been on power, income distribution, and conflict. The present result, in turn, implies that initially, growth must be reduced in order for firms to consider the possibility of switching to a clean production technique. Over time, therefore, the profits will begin to increase again toward the capitalists who are using clean technology.

References

Acemoglu, D., Aghion, P., Bursztyn, L., and Hemous, D. (2012). The environment and directed technical change. *American Economic Review*, 102(1):131–66.

Acemoglu, D., Akcigit, U., Hanley, D., and Kerr, W. (2016). Transition to clean technology. *Journal of Political Economy*, 124(1):52–104.

Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R., and Reenen, J. V. (2016). Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy*, 124(1):1–51.

Arthur, W. B. (2011). *The Nature of Technology: What it is and how it evolves.* Free Press.

Bowles, S. (2004). *Microeconomics: behavior, institutions and evolution.* Princeton University Press.

Bruvoll, A. and Larsen, B. M. (2004). Greenhouse gas emissions in norway: do carbon taxes work? *Energy Policy*, 32(4):493 – 505. An economic analysis of climate policy: essays in honour of Andries Nentjes.

Daly, H. E. (1991). *Steady-state Economics.* Island Press.

Duménil, G. and Levy, D. (1995). A stochastic model of technical change: An application to the us economy (1869–1989). *Metroeconomica*, 46(3):213–245.

Dutt, A. K. (1990). *Growth, Distribution and Uneven Development.* Cambridge University Press.

Foley, D. K. (2003). Endogenous technical change with externalities in a classical growth model. *Journal of Economic Behavior & Organization*, 52(2):167 – 189.

Foley, D. K. and Michl, T. (1999). *Growth and Distribution.* Harward University Press.

Gintis, H. (2009). *Game Theory Evolving: A problem-centered introduction to modeling strategic interaction (Second Edition).* Game Theory Evolving: A Problem-centered Introduction to Modeling Strategic Behavior. Princeton University Press.

Harrison, A., Hyman, B., Martin, L., and Nataraj, S. (2015). When do firms go green? comparing price incentives with command and control regulations in india. Working Paper 21763, National Bureau of Economic Research.

Kallis, G., Kerschner, C., and Martinez-Alier, J. (2012). The economics of degrowth. *Ecological Economics*, 84:172 – 180. The Economics of Degrowth.

Marglin, S. A. (1984). *Growth, Distribution and Prices.* Harward University Press.

Michl, T. R. and Foley, D. K. (2007). Crossing hubbert's peak: Portfolio effects in a growth model with exhaustible resources. *Structural Change and Economic Dynamics*, 18(2):212 – 230.

Myrdal, G. (1957). *Economic Theory and Under-developed Regions.* Gerald Duckworth & Co.

Nordhaus, W. D. (1973). The allocation of energy resources. *Broken Paper Series*, 1(3):529 – 570.

Nordhaus, W. D. (1994). *Managing the Global Commons: The economics of climate change.* MIT Press: Cambridge, MA.

Nordhaus, W. D. (2008). *A Question of Balance: Weighing the Options on Global Warming Policies.* Yale University Press: New Haven, CT.

Nordhaus, W. D. and Boyer, J. (2000). *Warming the World: Economic Modeling of Global Warming.* MIT Press: Cambridge, MA.

Scitovsky, T. (1954). Two concepts of external economies. *Journal of Political Economy*, 62(2):143–151.

Silveira, J. J. and Lima, G. T. (2008). Conhecimento imperfeito, custos de otimização e racionalidade limitada: uma dinâmica evolucionária de de ajustamento nominal incompleto. *Revista Brasileira de Economia*, 62(1):57–75.

Silveira, J. J. and Lima, G. T. (2016). Effort elicitation, wage differentials and income distribution in a wage-led growth regime. *Metroeconomica*, 67(1):44–75.

Stern, N. (2007). *The Economics of Climate Change: The Stern review.* Cambridge University Press.