UNIVERSIDADE DE SÃO PAULO
FACULDADE DE ECONOMIA, ADMINISTRAÇÃO E CONTABILIDADE
DEPARTAMENTO DE ECONOMIA
PROGRAMA DE PÓS-GRADUAÇÃO EM ECONOMIA

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DEVELOPING ENVIRONMENTAL AND ECOLOGICAL MACROMODELS

DESENVOLVENDO MACROMODELOS ECOLÓGICOS E AMBIENTAIS

São Paulo

2016

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Tese apresentada ao Programa de Pós–Graduação em Economia da Faculdade de Economia, Administração e Contabilidade da Universidade de São Paulo como requisito parcial para a obtenção do título de Doutor em Ciências.

Área de Concentração: Economia do Desenvolvimento
Orientador: Prof. Dr. Gilberto Tadeu Lima
Versão Corrigida

São Paulo

2016

FICHA CATALOGRÁFICA

Elaborada pela Seção de Processamento Técnico do SBD/FEA/USP

Oliveira, Guilherme de
Developing environmental and ecological macromodels / Guilherme de Oliveira. -- São Paulo, 2016.
114 p.

Tese (Doutorado) – Universidade de São Paulo, 2016.
Orientador: Gilberto Tadeu Lima.

1. Desenvolvimento econômico 2. Economia - Desenvolvimento 3. Sustentabilidade ambiental I. Universidade de São Paulo. Faculdade de Economia, Administração e Contabilidade II. Título.

CDD – 338.9

Para Maria Inês Quariniri e Joel de Oliveira (in memoriam) com amor.

Acknowledgements

I have incurred in many debts along the way to writing this Dissertation, which is the last act of my first long drama. My advisor, Gilberto Tadeu Lima has shaped most of what I have written in this work. While I owe him an incalculable debt, I am especially grateful for his detailed and patient comments to all versions. All that I can say is that *Poucas vezes eu vi alguém tão grande se fazer de tão pequeno na esperança de que os pequenos sejam grandes algum dia*.

I wrote part of this Dissertation at the University of Massachusetts - Amherst, and I would like to thank my sponsor at UMass, Peter Skott, for his detailed and fruitful comments on earlier drafts of each chapter. At UMass I would like to thank Arslan Razmi, Michael Ash, Raphael Gouvêa, Klara Zwickl, Leopoldo Gómez-Ramirez, João P. Souza and Emiliano Libman for all the hospitality. I had a great time in Amherst, so I should thank my family there: Jim Luippold, Raphael Gouvêa, Mariana, Xiaoyu, Lin, Lucy and Henry.

I spent countless fruitful hours discussing many of the issues dealt with in this Dissertation with Julia M. Costa and Thales Z. Pereira, and without such conversations this work would never have taken its present shape. Many thanks my dear friends.

I would like to thank USP and FEA for their fundamental role in my intellectual, academic and personal growth. My dear professors, colleagues and friends: Hugo Chu, Richard Simpson, Pedro G. Duarte, Renato Colistete, Fernando Rugitsky, Fernando Postali, José R. Chiappin, Vera Fava, Raúl Cristóvão, Laura Carvalho, Eleutério Prado, Kechi Hirama, Rodrigo Filev, Andre Roncaglia, Andre Mountian, Carlândia, Vivian, Rodger, Carlos, Elaine, Mariana, Neto and Gustavo Serra. I am extremely fortunate in the administrative assistance I have received along the way from Pinho, Leka and Cida. I should thank the financial support, at several stages and for different purposes, granted by FIPE, CAPES and CNPQ.

I have an incalculable intellectual debt with Adalmir Marquetti, André Pereira, J. Roberto Iglesias e Izete P. Bagolin. Many thanks for all the support and inspiration along these years. An especial thank also go to Henrique Blois, Denize Grzybovski, Marco A. Montoya, Thelmo Vergara, Paulo Jacinto, Jaylson Silveira, Carlos I. Drumond, Cleiton Silva, Viviane Santos, Giana Mores, Ricardo Lopes, Marília, Christiano Avanegra, Deise Bourscheidt, Lucas, Cassiano, Diegão, Jean, José Martins, Isabel, Cássia Ternus, Letícia Pedrini and my dear friend Fábio J. Piccinini. Thank you all.

I should thank my family in São Paulo: Thalez Z. Pereira, André Marques, Hugo Chu, Marcos Blumer, Mari and Gabi. Gostaria de agradecer o imenso apoio e carinho recebido da minha família em Passo Fundo: minha mãe, Maria Inês; pai, Joel de Oliveira (in memoriam); irmãs, Ana Paula e Elaine; e do restante da família, em especial: Mateus F. Antunes, Paulo, Maria, Marcos, Túlio, Lucas, Artur, Vó Cinira e Familia Baldi. Eu agradeço Marilice Baldi por seu constante suporte e doses subsequentes de interrupção e ajuda neste trabalho. I love you all.

Agradeço a compilação do código fonte em Latex disponibilizado pelo IAG USP.

“*Por amor as causas perdidas [...]*”

Humberto Gessinger

Resumo

OLIVEIRA, G. **Developing Ecological and Enviromental Macromodels**. 2016. 114 p. Tese (Doutorado em Economia do Desenvolvimento). Faculdade de Economia, Adminitracão e Contabilidade, Universidade de São Paulo, Brasil.

O objetivo desta Dissertação é desenvolver modelos macro que exploram implicações econômicas de algumas questões ecológicas e ambientais. O primeiro ensaio desenvolve uma extensão ambiental de um modelo Lewisiano de economia dual para explorar efeitos de longo prazo de uma regra de abatimento da poluição em países em desenvolvimento. Mostra-se que tal regra pode gerar uma armadilha de desenvolvimento ecológica. Contudo, esta economia pode ser libertada da armadilha não apenas por meio de um Big Push padrão, mas também por meio do que o ensaio chama de um Big Push Ambiental. O segundo ensaio apresenta uma extensão de um modelo *Harrodiano* que explora uma relação causal bidirecional entre meio ambiente e demanda efetiva em economias duais de baixa renda com níveis baixos de qualidade ambiental. Mostra-se que círculos viciosos perpétuos podem caracterizar o padrão de flutuações cíclicas da atividade econômica. O terceiro ensaio apresenta um modelo clássico-Marxiano que explora uma possível dinâmica de transição para a tecnologia limpa baseada em jogos evolucionários. Mostra-se que a heterogeneidade na distribuição de frequência das estratégias de adoção de tecnologia limpa e suja pode ser persistente. Um resultado em que todas, ou uma grande proporção de firmas adota a tecnologia limpa, é teoricamente possível, mas só será atingido com um choque inicial redutor de lucros sobre a distribuição funcional da renda e uma queda no crescimento econômico.

Palavras-chave: Desenvolvimento econômico; crescimento econômico; sustentabilidade.

Abstract

OLIVEIRA, G. **Developing Ecological and Enviromental Macromodels**. 2016. 114 p. Dissertation (Doutorado em Economia do Desenvolvimento). Faculdade de Economia, Adminitracão e Contabilidade, Universidade de São Paulo, Brazil.

The objective of this Dissertation is to develop alternative macromodels that explore macroeconomic implications of some environmental and ecological economics concerns. The first essay develops an environmental extension of a Lewis dual economy model to explore long-run effects of a pollution abatement rule in developing economies. It is shown that this pollution abatement requirement makes for the possible emergence of an ecological development trap. Meanwhile, this economy can be released from such a trap not only through a standard Big Push, but also by means of what the essay calls an Environmental Big Push. The second essay presents an extension of a *Harrodian* model of cyclical growth, which explores a bidirectional causal relationship between the environment and effective demand in dual low-income economies with relatively low levels of environmental quality. The model shows that perpetual vicious circles may characterize the pattern of fluctuations in economic activity. Finally, the third essay presents a classical–Marxian model that describes a possible transitional dynamics to clean technology based on evolutionary game theory. The results show that heterogeneity in the frequency distribution of strategies of the adoption of clean and dirty techniques may be a persistent outcome. 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 profit-reducing shock on functional income distribution and thus a fall in economic growth.

Keywords: Development economics; Economic growth; Sustainability.

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Chapter 1

Introduction

Clearly, the world of the twenty-first century is much more populated and has much higher 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, has been exerting an unprecedented negative influence on the environment so that the environmental degradation and anthropogenic climate change, more broadly, are now issues of public concern and central importance. Given their roots, they are important economic issues.

Most of the modern economic treatment of environmental issues is implicit or explicit based on an anthropogenic vision of *sustainable development* (SD). In a nutshell, a development is sustainable if it does not decrease the capacity to provide non-declining *per capita* utility for infinity (Neumayer, 2010). This utility can be formed by a set of different types of capital stock: physical, human, social and natural. The different existing visions on the subject can be roughly synthesized with regards to their assumptions about the aggregate capital stock: the "weak" and "strong" sustainability assumptions.[1]

The concept of weak sustainability (WS) derives from the work of Dasgupta and Heal (1974), Dasgupta and Heal (1980), Stiglitz (1974) and especially Solow (1974), Solow (1986), Solow (1991), Hartwick (1977), and Hartwick (1990) (the Hartwick/Solow rule). WS requires maintaining the total net investment, defined as involving all relevant forms of capital, above or equal to zero, or in other words, keeping the total value of physical and natural capital constant. To achieve SD, the Hartwick/Solow rule consists of the following assumptions: Resources are abundant; there is infinite substitution among all

[1] This anthropogenic and materialistic perspective is not unique. For a different perspective see, for example, Abramovay (2015).

forms of capital; and technological progress can overcome any resource (environmental) constraint. Another important implicit assumption is that all negative environmental impact is reversible, given the technological opportunities available in a capitalist economy.

In this Dissertation, strong sustainability, SS, is understood as a non-substitutability paradigm according to which physical capital is not a perfect substitute for natural capital. In addition, natural capital must remain at least constant for infinity. Following Turner and Pearce (1993), the main factors contributing to the non-substitutability assumption are that we are largely uncertain about the consequences of the overexploitation of natural capital; the negative environmental impact on natural capital is irreversible; and basic natural capital is the support for many life functions on Earth.

The first formal distinction between WS and SS is credited to Pearce et al. (1989). David Pearce has also provided arguments for SS in Pearce et al. (1990) and Turner and Pearce (1993). The list of those who helped to define SS is large, and I mention only some important figures: Jacobs (1991), Spash (1993), Daly (1991) and Costanza and Daly (1992). Understandably, a significant characteristic of SS is interdisciplinarity, which makes it difficult to agree on a general definition. For most ecological economists, WS and SS may also be associated with different fields in applied and theoretical economics: *environmental* and *ecological* economics, respectively.

These assumptions underlie the answers to one of the most important questions in economic theory: Are there limits to growth? In the past, answers were articulated in the context of natural resource exploitation. In environmental economics, and therefore under the WS assumption, most positions defend that there are no limits to growth, and indeed, sustainability "has nothing necessarily to do with growth" (Solow, 1991, p. 179).[2] In this context, some may agree with Solow (1991) that the preferences of the future generation are unknown and that we should focus in WS. However, it has become clear that limits to growth may not arise from natural resource exploitation, but rather from the limited capacity of nature to act as sink for capitalist wastes so that it is reasonable to believe that people in the future would prefer to breathe clean air and to drink fresh water.

These new contours for the relation between economic growth and the environment raises new versions of old challenges. Does capitalism have a strong tendency toward a steady state of full employment with decreasing negative externalities on the environ-

[2] For contributions in this unending controversy see, for example, Meadows et al. (1972), Solow (1974).

ment? Are developing countries capable to adopting clean technology to achieve the same living standards of rich countries without destroying the planet? Both are macroeconomic questions.

Environmental economics has addressed related issues, and important contributions, such as the Green Solow model (Brock and Taylor, 2010), have attracted great attention.[3] Recently, however, Rezai et al. (2013) and Rezai and Stagl (2016) raised an important point. In comparison with environmental economics, ecological economics has not been paying enough attention to the macroeconomic level both in terms of theory and modeling. In fact, key topics debated in the field, such as sustainable consumption, a reduction in working time, the Degrowth debate, and so forth, require a macroeconomic perspective. They call for a conciliation between ecological economics and post-Keynesian theory. As important as this conciliation may be, I am not sufficiently convinced that the statement should not be the opposite as well: Heterodox macroeconomics has largely neglected ecological (and, indeed, environmental) issues.[4]

In fact, a close look at the history of economic ideas reveals that, ironically, alternative macromodels have by a large neglected sustainability issues. This is ironic because a set of theories concerned with the demonstration that what neoclassical theory calls "market failures" are, in fact, the normal state of affairs, left the perhaps most important *coordination failure* in a second plan. While great names of the economics profession, such as Solow (1974) and Stiglitz (1974), for instance, tried to demonstrate that economic growth is compatible with the optimal inter-temporal rate of exploitation of natural resources, most heterodox economists were out of the debate.[5]

The point would be simply that answers to the new challenges mentioned above are sensitive not only to the sustainability assumptions but also to the internal consistence of macroeconomic theories. Therefore, it does not logically follow that one should focus on conciliating ecological economics with heterodox macroeconomics in order to describe sustainability issues. In fact, as heterodox theory, it is more promising to address the environmental challenges from both sustainability perspectives. As a matter of logic, it is much more strong, for example, to demonstrate that there is no stable and well-behaved

[3] See also Stokey (1998), Copeland and Taylor (1994).

[4] As a matter of logic, the causality is relevant, of course.

[5] It is beyond the scope of this Dissertation to discuss the reasons for this silence. Of course, the qualification is important since some exceptions always exist.

tendency toward a steady state with full employment and decreasing pressures on the environment under WS than SS assumptions.

Obviously, this does not exclude the important conciliation between post-Keynesian with ecological macroeconomics. It just amplifies the alternative modeling set.[6] One may argue, for example, that the Georgescu-Roegen (1971) thermodynamics equilibrium contribution, followed by many ecological economists, can be more compatible with a classical description of the economic system than an aggregate structuralist approach.[7] In turn, post-Keynesian economics may describe very well how fluctuations in economic activity are affected by environmental policies, such as the cap and trade system (an instrument proposed by environmental economics), or the reduction in working time and so forth.

I shall argue in each chapter of the present Dissertation that it is possible to accommodate explicitly or implicitly both sustainability assumptions in heterodox macroeconomic frameworks of cyclical fluctuations, economic growth and development economics. Of course, simplifying assumptions that sometimes differ from the original contributions, especially in ecological economics, is necessary: Otherwise, steady-state macromodels may become analytically intractable.

These theoretical aspects and the search for answers for some environmental issues fundamental to economic and political decision-making motivated this analysis, whose general purpose is **to develop alternative macromodels that explore, in some of their many relevant aspects, macroeconomic implications of some environmental and ecological economics concerns**. The present Dissertation pursues this general goal throughout three *independent* and *self-contained* theoretical essays, which explore the following concerns: economic effects of a stylized environmental policy in developing countries; the emergence of endogenous cyclical fluctuations; and the role of clean technical change.

There is some general consensus in the environmental and ecological literature that the relationship between macroeconomy and the environment remains relatively unclear.[8]

[6] Foley (2003) and Michl and Foley (2007), for example, present interesting classical-Marxian models addressing environment-saving technological change.

[7] Foley (2004) interprets the classical view as a thermodynamics equilibrium and also as a complex system.

[8] See, for example, Brock and Taylor (2004).

The economics profession has only a limited understanding of the basic behavior of the environment and very limited high-quality data. Because of these shortcomings, it is particularly relevant to develop a set of relatively simple theoretical macroeconomic models that generate logical and robust predictions.

The present Dissertation is addressed not only to the audience of heterodox macroeconomists, but also to scholars of ecological and environmental economics, as well as to a more neoclassical tradition. My general contribution aligns with this recent movement to model sustainability issues in heterodox macromodels.[9] Along the way, I hope to show that alternatives and internally plural perspectives can give precise and new contributions.

Finally, one may wonder, of course, why the concern with developing environmental and ecological heterodox macromodels. The answer is simply that it seems illusory to believe that one universally applicable framework, the neoclassical one, is suitable and has answers for all environmental problems.[10] Pluralism is beneficial for any environmental question at hand, and as in other contexts, a set of models must be adapted to any of them so that the dominance of a particular framework should not to be desired by its own sake.

The structure of this dissertation is as follows. Chapter 2 presents the first essay, which extends a Lewis dual economy development approach to explore the very timely issue of the interaction between environmental quality and economic growth. The development framework is set under WS assumptions. The chapter was influenced by the recent and relevant contribution of the so-called "green Solow model," set forth in Brock and Taylor (2010). The green Solow model shows the existence of a steady state of full labor employment with diminishing negative externalities on the environment. The result is achieved throughout an abatement mechanism that consumes a fraction of aggregate production, which, even though it lowers savings, does not prevent any particular country from achie-

[9] See the especial issue of Ecological economics in Rezai and Stagl (2016). See also Foley (2003), Michl and Foley (2007), Fontana and Sawyer (2013) and Dafermos et al. (2014).

[10] A word about labels: It is always difficult and noisy to confine a set of relevant models in just one subset, but I will shall refer to "neoclassical" as the subset of models or frameworks that follow the Walrasian general equilibrium paradigm. Consequently, alternative (or heterodox) models are the remaining subset, especially: Classical–Marxian, post-Keynesian, Ricardian (Sraffian), Kaldorian, Harrodian and other macromodels that formalize the pioneers of economic development. This definition is close to the one adopted by Setterfield (2010).

ving such a sustainable steady-state level.

The essay asks whether developing countries are not structurally any different in the sense that such an abatement mechanism can prevent them from achieving economic maturity and thus such a sustainable level. Although subject to the limitations of an analysis based on a stylized economy, the main qualitative results contribute to shed light on ongoing heated political discussions about whether developing countries can simultaneously stimulate economic growth and reduce negative externalities on the environment. In fact, a similar question underlies one of the most recent international round of negotiations on climate change, just held at the 2015 Paris Climate Conference. More than 190 developed and developing countries agreed that they need to collectively chip in by curbing greenhouse gas emissions responsible for global warming. To the best of my knowledge, our green Lewis development approach proposed in the first essay is the first theoretical model that formalizes such an issue.

Chapter 3 presents a *Harrodian* model that incorporates an ecological dimension. It examines implications for a low-income developing country with relatively low levels of environmental quality of the flexibility of a questionable assumption of the environmental Kuznets curve, EKC, which predicts an unidirectional causal correlation from economic growth to environment. In line with a relevant literature, the chapter suggests that the behavior from the environment should also be considered to affect economic growth.[11]

In such developing countries, this causality channel may assume the form of environmental adjustment costs. However, instead of assuming solely a long-run relationship, the essay argues that these adjustment costs are also binding in the medium run so that we should also pay attention to endogenous cyclical fluctuations that arise from these ecological constraints. In this context, under reasonable parameters, we show that perpetual cyclical growth may characterize these economies. From a theoretical macroeconomic perspective, it is demonstrated the existence of a steady state in which capital accumulation is compatible with a "natural growth rate," the environment intrinsic growth rate. The instability of capital accumulation raised by effective demand is now accommodated by variations in the level of environmental quality.

Chapter 4 explores the adoption clean technical change, which was absent in the previous chapters for analytical and theoretical purposes. The literature context of the essay

[11] See, for example, Stern (2007) and Dasgupta et al. (2002).

is the economic models of climate change, such as that of Nordhaus (2008). As pointed out by Acemoglu et al. (2012), Aghion et al. (2016) and Acemoglu et al. (2016), it has been largely unsatisfactory to treat the adoption of clean technology as exogenously given in these models. The essay proposes a novel behavioral foundation for the process of the adoption of clean technology, in which agents are heterogeneous and make strategic decisions based on historical learning.

This behavioral foundation co-evolves with a classical-Marxian description of the macroeconomy. The contribution of the model lies in the description of what accounts for the diffusion and maybe the non-use of available clean techniques in a competitive environment. For reasonable parameters values, the model shows that heterogeneity in the frequency distribution of the adoption strategies of clean and dirty techniques may be a persistent outcome, either in response to pecuniary externality effects or public policy. The model also explores several economic impacts in terms of income distribution and economic growth along these transitional dynamics to clean technology.

Chapter 5, finally, summarizes the main contributions and limitations of this Dissertation, as well as related questions and issues left for future research.

Chapter 2

A Green *Lewis* Development Model

2.1 Introduction

In recent years there has emerged considerable, if not conclusive, scientific evidence that anthropogenic greenhouse gas (GHG) emissions accelerate the natural process of climate change on Earth (IPCC, 2014). Environmental economics has incorporated such evidence, and its consequences, in macroeconomic models of optimal exploitation of natural resources, for instance, Solow (1974). However, the literature has not paid sufficient attention to the limited ability of the planet to act as a sink for capitalist waste, and the challenge that it poses to economic growth and development theory.

A notable exception and important contribution is "The Green Solow Model" set forth in Brock and Taylor (2010).[1] This work is an elegant combination of Solow (1956) model and the Environmental Kuznets Curve (EKC). The authors start with a technology that combines capital and labor to produce a single good through constant returns to scale, which in turn generates emissions that must be mitigated through an abatement mechanism. As the production function is concave, given the assumption of diminishing marginal returns to capital, externalities also exhibit a non-linear pattern in the inverted U-shaped format - the EKC. This formalization contributes to improve the estimation quality of convergence in *per capita* CO_2 emissions, one of the main motivations of the paper.

The Green Solow model has an optimistic message to developing countries. It suggests that it may be enough to allocate a fraction of economic activity to abatement while, at same time, the economy accumulates capital to improve the level of environmental quality and *per capita* income. There is no any endogenous force in such environmental policy that

[1] See Copeland and Taylor (1994), and Stokey (1998) for other examples.

can qualitatively compromise the transition of a particular country to the steady state.[2]

This message confronts a political argument of many developing countries that see restrictive instruments for environmental control, such as emission targets, as an obstacle to economic development, which can prevent them from achieving the economic level of developed, rich countries (Green et al., 2014). Based on these interregional justice arguments, the political view that is gaining prominence is that without international environmental compensations policies, developing economies will be unable to have higher growth rates while at the same time reducing their emissions.[3] By contrast, the Green Solow model seems to imply that designing compensation policies for developing countries is not necessary.

Recent econometric evidence suggests that pollution costs are already high in many economies, as it has been found, for instance, that exposure to a poor environment can decrease labor productivity (Graff Zivin and Neidell, 2012), and has long-term consequences on health and human capital (Currie et al., 2009). Thus, for some developing countries, a direct implementation of the abatement mechanism embodied in the Green Solow model would imply in a steady decrease of environmental quality over the subsequent decades, which might compromise capital accumulation and economic development. Along with pollution costs imposed by abatement targets, such mechanism may result in a fall of savings, which in turn, may create economic conditions for the formation of a new source of development trap in developing economies.

This particular feature is not captured by models *a la* Solow (1956), since such models, given several of their assumptions, is best seen as describing the pattern of economic growth in mature economies, unlike the models in the tradition of the pioneers of economic development, such as Nurkse (1952), Rosenstein-Rodan (1943), and, especially, Lewis (1954). In their view, in developing economies, among other structural features, the labor force is usually not a binding constraint, capital accumulation is not necessarily subject to diminishing returns, and natural resources play an important role. These structural characteristics are still found, *mutatis mutandi*, in many developing countries, and can crucially

[2] Brock and Taylor (2010, p. 136) are careful enough to mention that such conclusions are valid in a context in which the intensity of abatement is fixed, and "there are no political economy or intergenerational conflict to resolve".

[3] See Nagashima et al. (2009) and Verbruggen (2009) for some discussions on and simulations of international environment agreements.

affect the pattern of convergence to the steady state with achievement of maturity through the emergence of development traps.

Thus, the economic implications that arise from the standard prediction of the Green Solow model pose a natural question: are not developing countries structurally any different? In other words, is the dynamic of long-run convergence to the steady state with achievement of maturity any different for a developing economy, in the sense that a simple environmental policy can prevent them from achieving the mature phase? In this context, the main goal and contribution of this paper is to develop a "green" extension of a Lewis dual economy model, in which the macroeconomy and the environment interact, thus illustrating some of the structural characteristics and mechanisms mentioned above.

These issues are explored using a similar framework to the Green Solow model, but in a developing macroeconomics context, inspired in Ros (2013). It is shown that abatement policies without international compensation mechanisms may result in an *ecological development trap*, from which a developing economy, if left to the free play of its structural forces, may never escape, a prediction in the spirit of the pioneers of development economics. Despite this potentially pessimistic message, it is also shown that in some particular cases, exogenous compensation strategies can help developing countries to get (back) on track to maturity, even if a long track, through either a standard Big Push, or what we call an *environmental* Big Push.

The remainder of the paper is organized as follows: Section 2.2 describes the general framework, and Section 2.3 presents the building blocks of the model. Section 2.3.1 analyzes the behavior of the model in the long run. The balanced growth and (in)stability conditions are qualitatively analyzed in subsection 2.3.1.1, in which a possible configuration of multiple equilibria and development trap is explored. The paper closes with a summary of the main conclusions derived along the way, and some final comments.

2.2 General framework

The model presented in the subsequent section is a Lewis dual economy model in which the environment plays an important role. To understand the general framework, consider an economy that is closed and has no explicit fiscal activities. In addition, suppose that this economy follows a pollution abatement rule, which is defined by the government according to some level of negative externalities on the environment that must be mitigated.

The dualism is represented by two sectors that produce a single good used for both consumption and investment: the Traditional T and the Modern M. Moreover, there are two possible phases of development: the surplus labor (or underdevelopment) phase and the mature (or developed) phase. The underdevelopment is characterized by the coexistence of the two sectors and, therefore, as the T sector is a reserve of abundant labor, also by an unlimited supply of labor to the M sector. Meanwhile, the developed phase, or maturity, begins when the T sector ceases to exist and, therefore, the supply of labor to the M sector becomes inelastic as in the Solow (1956) model.

The M sector combines physical capital with labor in a Cobb-Douglas production function with constant returns to scale, jointly producing the M-good and a flow of pollution. A governmental authority requires the M sector to dedicate a fraction of its production to abatement. This fraction is calibrated according to a rule that is endogenous to the level of environmental quality.

When the economy is in the underdevelopment phase, it is supposed that the amount of negative externalities comes from the production process of a local urban M sector. In addition, such economy is exogenously affected by the level of negative externalities generated by developed countries, through a mechanism of pollution transfer. In such case, the sensitivity of a developing country to this international problem is inversely related to its level of economic development: the less developed is the economy, the greater is its sensitivity to this pollution transfer. Once maturity is achieved, it is supposed that this negative effect ceases. For simplicity, this pollution transfer is treated as exogenous, and free of any monetary compensation mechanism.[4]

Some real–world features on the interaction between the environment and development seems to justify such simple theoretical assumption. Jacob and Marschinski (2013), for example, argue that most industrialized countries are net importers of carbon emissions, that is, they release fewer emissions for the production of their total exported goods and

[4] An important aspect of environmental externalities takes place in a global scale, in which the weak capacity of developing countries to adapt to climate change may play an important role. However, as this model is a one-country model, we abstract from more complex pollution interactions between countries. See Razmi (2015) for a model that explores similar environmental dynamics in a North-South economic context.

services than the amount generated by their developing countries trading partners for producing their total imported goods and services. In this sense, the negative environmental impact embodied in trade can be seen as a mechanism of pollution transfer. Another well-documented pollution transfer mechanism is the international trade in waste products, which has been negatively affecting especially developing countries in Africa. Exploring such an evidence, Copeland (1991), for instance, developed a model to analyze the welfare effects of international trade in waste products in the presence of illegal disposal. The author argues that taxation to control externalities associated with waste disposal in this economies can be welfare improving.

To complement this dualism, it is supposed that the T sector houses a surplus labor that is large enough to ensure an infinitely elastic supply of labor in both sectors at the subsistence wage, which in turn, is equal to the average product of effective labor in the T sector (Lewis, 1954). For simplicity, it is supposed that the pollution in the T sector is negligible. Wages in the M sector are determined by the wages in the T sector, plus a wage premium that must be paid to attract workers from the Traditional sector. This wage premium compensates for any economic and psychological costs of migrating. The Lewisian dualism persists until the T sector disappears when all workers are attracted to the M sector, and the supply of labor becomes inelastic to wages.

The environmental dimension is represented by an index of environmental quality, ϵ. Therefore, the pollution generated by the M sector reduces the level of environmental quality in the economy. It is supposed that if this negative impact is persistent, the exposure to a poor environment can lower labor productivity, through health and cognitive channels. To model this effect, we specify a process of labor–augmenting technical change that is endogenous to the level of environmental quality.[5]

This latter assumption is based on recent robust empirical evidence, such as that provided by Graff Zivin and Neidell (2012), who found a causal relation between the variations in the atmosphere ozone concentration and the labor productivity of American farmers. They find that a 10 ppb (parts per billion) decrease in ozone concentration increases labor productivity by 5.5 percent. Chang et al. (2014) find similar results for industrial workers:

[5] The negative externalities on the environment should not be thought of exclusively as carbon dioxide CO_2 emissions, but as a set of pollutants, or environmental degradation in general, that may lower labor productivity.

the reduction of an outdoor pollutant increases the labor productivity, measured as the average time of tasks. In both cases, the authors argue that pollution control policies can be seen as an investment in human capital.

In global terms, Kjellstrom et al. (2009) have forecasted that the climate change effects, measured in terms of increase in average temperature, may negatively affect labor productivity, an effect that may be heterogeneously distributed across regions. They argue that the lost labor productivity will be greater in Southeast Asia, Central America, and the Caribbean, given the more intense heat in those locales. From the industrial side, Berman and Bui (2001) use an estimation of the total factor productivity and find positive effects of environmental regulation on productivity at a set of refineries in Los Angeles (USA) from 1972-1992, despite the high cost of abatement technologies.

The causality channel through which the environment affects labor productivity occurs through observable and unobservable effects, such as effort, health, and cognitive abilities (Graff Zivin and Neidell, 2013). The most direct observable impact may be the improvement in occupational health in terms of internal firm effects, which includes reorganization of the production process (Delmas and Pekovic, 2013), and also external effects, such as reducing air pollution (Chang et al., 2014).

These effects are also latent in the long run; for instance, Currie et al. (2009) examine the effects of pollutants on school attendance and find that the increase in carbon monoxide (CO) emissions, even when below federal air quality standards, significantly raises absences. Their results suggest that the substantial decline in CO levels over the past two decades has yielded economically significant health benefits, which also have consequences for future generations.

It is important to keep in mind that the environmental dimension is included in this dual economy model via the interaction between negative externalities from the M sector, and the positive effects of environmental quality on labor productivity and savings. However, Lewis (1954, 1955 and 1958) was not explicitly concerned with the impact of economic growth on natural resources but rather the opposite. In addressing the issue of the scarcity of natural resources, Lewis (1955) referred to Malthus and Ricardo, his classical inspirations, which had a pessimistic view. In this sense, this green extension enriches the 60-year-old Lewis model with a modern notion about environmental economics.

It is now possible to build on this intuitive discussion to flesh out the model in stages, starting with the baseline structure.

2.3 The model

The model starts by considering that the M sector jointly produces two outputs: the M good and a flow of pollution, z. Hence, the production of every unit of M generates some level of externalities, but following Copland and Taylor (2005), the amount of pollution released in the environment will differ from the amount generated if there is abatement. In the present instance, however, the fraction of M output dedicated to abatement, ϕ, is determined by an environmental authority, and it is not a choice variable of the firm. Increases in ϕ reduce the net flow of pollution, but at the cost of, say, primary inputs from M production. Equivalently, it is possible to interpret the M sector as producing a given level of gross output, and using a fraction ϕ to abatement. This leaves the M sector with a net output to be sold in the goods market which is given by:

$$M = (1 - \phi)K^{\alpha}(\xi L_M)^{1-\alpha}, \tag{2.1}$$

in which M, L_M, and K are output, employment, and capital stock in the M sector, with $0 < \alpha < 1$, while ξ is a labor productivity measure.[6] The level of this productivity measure is given by $A\epsilon$, where A represents the level of technology and ϵ denotes the level of environmental quality. Therefore, the growth rate of this productivity measure is given by the growth rate of the environmental quality, $\hat{\epsilon}$, plus an exogenous growth component, σ:

$$\hat{\xi} = (\sigma + \hat{\epsilon}). \tag{2.2}$$

In the Solow exogenous growth model a similar effect represents the state of technology only, which grows exogenously, and in the present instance, such exogenous growth is captured by σ. We are augmenting this interpretation to feature changes in labor productivity being also affected by changes in the environmental quality. In line with the empirical evidence, which finds a negative association of pollution and labor productivity, we suppose

[6] Note that in such circumstances, the abatement technology uses the same factor intensity as the Modern sector. Copland and Taylor (2005) show that this is an easy way to capture the notion that abatement is costly, but avoids the complexity of modeling another sector, and/or another technology.

that the accumulation of environmental quality creates conditions for an expansion of this productivity measure, ξ (a property of the labor force). We are augmenting the standard prediction of EKC to capture the possibility of reverse causality between environmental quality and economic growth, which is one of the sources of pollution costs in the model. Thus, it is supposed that the levels of technology and environmental quality jointly determine labor productivity.

Another source of cost is measured by ϕ, the fraction of the M product that must be dedicated to pollution abatement, which is made endogenous to the level of environmental quality, and is defined according to the following rule:

$$\phi = (1 - \epsilon/E), \tag{2.3}$$

where E is a maximum attainable level of environmental quality, which is used by the government authority as a benchmark in the abatement rule.[7] The level of E is given exogenously by intrinsic characteristics of the environment. It is supposed that the environmental authority is risk averse, and committed to the biophysical limits of the planet, taking into account the maximum attainable level of environmental quality. When the current level of environmental quality falls below E, the government requires that the M sector uses a fraction of the M output in the abatement activity. Given the specification in (2.3), the current level of environmental quality, ϵ, cannot be higher than its maximum attainable level, while the abatement activity only ceases with $\epsilon = E$.

In the surplus labor phase, the actual amount of pollution released in the environment is given by the net flow of domestic negative externalities plus the pollution coming from developed countries, which ceases at the mature phase. The corresponding functions (in intensive units, $k \equiv K/\xi L$) in each development phase are defined as follows:

$$z_U = (\gamma_1 - \gamma_2\phi)k^{\mu} - \gamma_0, \tag{2.4}$$

$$z_M = (\gamma_1 - \gamma_2\phi)k^{\mu}, \tag{2.5}$$

in which γ_0 is an exogenous pollution parameter, γ_1 is a catch coefficient, which measures the negative impact of k on the environment, and γ_2 is a productivity parameter that

[7] Therefore, $\lim \phi_{\epsilon/E\to 0} = 1$, and $\lim \phi_{\epsilon/E\to 1} = 0$.

measures the M sector's efforts at abatement, all these parameters being strictly positive. As the negative externalities are a joint production mechanism, μ is a scale effect, which is equal to 1 along the surplus labor phase, and to α in the mature one, in line with the effect of capital intensity in efficiency units in a general Lewis model (Ros, 2013). Hence, we follow a similar optimistic scenario for the EKC as modeled in Brock and Taylor (2010).

When the M and T sectors coexist they produce the same good. This single good, which is sold in a competitive goods market, and whose price is normalized to unity, is produced in the T sector under constant returns to scale:

$$T = \xi L_T, \tag{2.6}$$

where T and L_T are the output and employment in the T sector. It is supposed that the productivity of the labor force employed in the T sector is also affected by the level of environmental quality. However, as it is solely the (capital-using) production in the M sector which generates a flow of pollution, the pollution abatement rule in (2.3) does not apply to the T sector. For the sake of simplicity and tractability, we further assume that the productivity measure represented by ξ refers to the entire labor force, regardless of the sector where it is employed. Therefore, the specification in (2.2) applies to the effective labor in the T sector as well, which means that we are implicitly assuming that the T sector is also subject to the exogenous growth of labor productivity given by σ. Finally, we assume that there is no open unemployment, $L = L_T + L_M$, with the labor force growing at the exogenous rate $n > 0$, in both development phases.

In the surplus labor phase, the marginal product of effective labor in the T sector is constant, and thus the average product of effective labor, $T/\xi L_T$, remains constant as well. The M sector hires labor from the T sector by paying a constant wage premium, $f - 1$, over the average product of effective labor in the T sector, so that $w = f w_T$. Since f is constant, the wage premium can be normalized to zero (so that $f = 1$) without it making any significant qualitative difference to the analysis that follows. Therefore, it follows that $w = 1$, and the labor force does not constrain capital accumulation for as long as the two sectors coexist.

When maturity is reached, labor supply becomes inelastic, and the present Lewis model behaves like the Solow (1956) model. In this phase, workers receive a wage equal to their marginal productivity. Thus, from the competitive labor and capital market equilibrium conditions, and profit-maximizing behavior on the part of the firms in the M sector, it follows from (2.1) that:

$$r = \alpha(1-\phi)^{1/\alpha}[\frac{1-\alpha}{w}]^{\frac{1-\alpha}{\alpha}}, \tag{2.7}$$

$$w = (1-\alpha)(1-\phi)[\frac{K}{\xi L_M}]^{\alpha}. \tag{2.8}$$

Note that the profit rate in (2.7), r, depends on the real wage in both phases of development. From (2.7) first with $w = 1$ and $L_T > 0$, and then with w being determined by (2.8), and $L_T = 0$, respectively, the profit rate in each developing phase is given by:

$$r = \alpha(1-\phi)^{1/\alpha}(1-\alpha)^{\frac{1-\alpha}{\alpha}}, \tag{2.9}$$

$$r = \alpha(1-\phi)k^{\alpha-1}. \tag{2.10}$$

The existence of surplus labor counterbalances the operation of the decreasing marginal returns to capital, but the net result depends on (2.3). In the mature phase, the profit rate depends negatively on k. Capital accumulation in the M sector raises labor demand, but the supply of labor is now inelastic, and the available labor force becomes a binding constraint.

From these structural equations, a comment as regards the notion of Sustainable Development (SD) discussed in the environmental literature (e.g. Neumayer 2010) is in order. In the present instance, SD is the capacity to provide non-decreasing utility for future generations. The arguments of such implicit utility function include physical capital, and some level of environmental quality. It is supposed that natural and physical capital are substitutes and that all negative environmental impact may be reversible in the very long run. Therefore, this economy is modeled under the weak sustainability (WS) assumption.

In what follows, we describe the long run dynamics, when it is assumed that the economy is moving over time, with the state variables being the capital-labor ratio in efficiency units, k, and the level of environmental quality, ϵ.

2.3.1 The environmental and macroeconomic dynamics

In the present instance, the environmental quality is modeled in a broad sense, abstracting its capacity of reproduction or intrinsic growth, and in this sense, we follow a similar approach as the one followed in the Green Solow model. First, it seems implausible not to take into account the environmental capacity of regeneration, but when we consider that *natural* environmental changes occur over a very long time horizon, generally $200-400$ years, it seems more plausible not to include these natural changes in a dynamic system that includes capital accumulation functions with shorter time horizons.[8]

Therefore, the level of environmental quality changes according to the negative influence of the flow of pollution in each development phase. Using (2.3), (2.4) and (2.5), such dynamics are given by:

$$\frac{d\epsilon}{dt} = [(\gamma_2(1-\epsilon/E) - \gamma_1)k - \gamma_0]\epsilon, \tag{2.11}$$

$$\frac{d\epsilon}{dt} = [(\gamma_2(1-\epsilon/E) - \gamma_1)k^{\alpha}]\epsilon. \tag{2.12}$$

Recall that in the surplus labor (maturity) phase we have $\mu = 1$ ($\mu = \alpha$). As regards γ_0, in the mature phase the economy stops receiving transfer of foreign pollution, and thus $\gamma_0 = 0$. Note also that we make the change in environmental quality to depend on the level of capital-labor ratio in efficiency units, and not solely on capital accumulation. In fact, empirical evidence presented in Marquetti and Pichardo (2013) suggest that labor intensive economies, and thus economies with lower capital-labor ratios, emit less CO_2. Hence, it seems that it is not the amount of production, but the way that a particular economy produces, with more or less dirty capital stock *per* worker, that matters the most when it comes to model pollution dynamics.

The dynamics of the capital-labor ratio in efficiency units is given by:

$$\frac{dk}{dt} = srk - (n + \hat{\xi})k, \tag{2.13}$$

in which firm-owner capitalists save a given fraction, s, of their profits in efficiency units of labor, given by rk. In addition, we assume, just for simplicity, that capital does not depreciate over time, whereas n is the population growth rate, taken as exogenous. By definition, the proportionate rate of change of labor-augmenting technical change, $\hat{\xi}$, negatively affects k.

[8] In general, when this intrinsic growth is take into account it is used a logistic function to model environmental dynamics. Theoretical and practical modeling discussions can be found in Arrow et al. (1995) and Brander and Taylor (1998), respectively. This analytical strategy is avoided here to maintain the model analytically tractable.

As with the level of environmental quality, the dynamics of the capital-labor ratio in efficiency units will vary according to each development phase. Therefore, first substituting (2.3), (2.4), and (2.9) into (2.13) under $T_S > 0$, and then substituting (2.3), (2.4) and (2.10) into (2.13) under $L_T = 0$, we have:

$$\frac{dk}{dt} = \Omega k(\epsilon/E)^{1/\alpha} - (n + \sigma + \hat{\epsilon})k, \tag{2.14}$$

$$\frac{dk}{dt} = s\alpha k^{\alpha}\epsilon/E - (n + \sigma + \hat{\epsilon})k, \tag{2.15}$$

where $\Omega = s\alpha(1 - \alpha)^{(1-\alpha)/\alpha}$. Note that the level of environmental quality affects the capital-labor ratio in efficiency units both positively, by decreasing the fraction of M output allocated to pollution abatement, and negatively through labor-augmenting technical change. The latter also defines the scale effect over the surplus labor phase, as discussed later on.

2.3.1.1 Balanced growth and (in)stability

The existence of these two development phases raises the possibility of multiple equilibria along the development path. Assuming that $\epsilon < E$, we can compute these equilibria given by $\dot{k} = (dk/dt) = \dot{\epsilon} = (d\epsilon/dt) = 0$. First, with the labor force being infinitely elastic at the subsistence wage in the underdevelopment phase, we have the following unique pair of economically relevant (that is, strictly positive) equilibrium values:

$$k_U{}^* = \frac{\Omega^{\alpha}\gamma_0}{(\gamma_2 - \gamma_1)\Omega^{\alpha} - \gamma_2(n + \sigma)^{\alpha}}, \tag{2.16}$$

$$\epsilon_U{}^* = [\frac{n + \sigma}{\Omega}]^{\alpha} E. \tag{2.17}$$

Even under weak sustainability assumptions the conditions for the existence of a positive real solution are very specific.[9] As all parameters values in (2.16) and (2.17) are strictly positive, a strictly positive value for k_U requires $(\gamma_2 - \gamma_1)\Omega > \gamma_2(n + \sigma)$, which implies that abatement productivity must be higher than the catch coefficient. Note that the necessary condition given by $(\gamma_2 > \gamma_1)$ is similar to the assumption of sustainable growth which appears in Brock and Taylor (2010), but in that case, it is the technological

[9] In general, models with *strong* sustainability assumptions are not fully compatible with equilibrium models, since the biophysical limits of the planet are modeled according to the laws of thermodynamics.

progress in abatement that must exceed growth in aggregate output in order for the flow of pollution to fall and the level of environmental quality to improve.

Regarding ${k_U}^*$, the higher the parameters associated with negative externality effects, γ_0 and γ_1, the higher the ratio of capital to effective labor in equilibrium. The same is true for n and σ. Meanwhile, the greater is the abatement effort, the lower is the equilibrium value for k. As we have defined the change of ϵ as governed by anthrogenic reasons, the opposite is true for ${\epsilon_U}^*$. Note also that the greater is the maximum attainable level for the environment, the greater is the steady-state value of environmental quality in the surplus labor phase, as further discussed later on.

The system of differential equation in (2.11) and (2.14) can be analyzed through a Taylor's expansion of the form $\dot{x_i} - {x_i}^* = J_U(x_i - \dot{x_i})$, in which J_U is the corresponding *Jacobian* matrix, and $\dot{x} \equiv \partial x/\partial t$. The properties of the system can be qualitatively analyzed using local stability criteria. The *Jacobian* matrix, J_U, is given by:

$$J_U = \begin{bmatrix} -[\frac{\gamma_2 k^*}{E}]\epsilon^* & [\gamma_2(1-\epsilon^*/E) - \gamma_1]\epsilon^* \\ [\frac{1/\alpha\Omega\epsilon^{*(1-\alpha)/\alpha}}{E^{1/\alpha}} + \frac{\gamma_2 k^*}{E}]k^* & -[\gamma_2(1-\epsilon^*/E) - \gamma_1]k^* \end{bmatrix}.$$

Thus, using the corresponding equilibrium values it follows that:

$$J_{U_{11}} \equiv \frac{\partial\dot{\epsilon}}{\partial\epsilon} = -\frac{\gamma_2\gamma_0(n+\sigma)^\alpha}{(\gamma_2-\gamma_1)\Omega^\alpha - \gamma_2(n+\sigma)^\alpha} < 0,$$

$$J_{U_{12}} \equiv \frac{\partial\dot{\epsilon}}{\partial k} = \frac{(\gamma_2-\gamma_1)\Omega^\alpha - \gamma_2(n+\sigma)^\alpha}{\Omega^\alpha}[\frac{n+\sigma}{\Omega}]^\alpha E > 0,$$

$$J_{U_{21}} \equiv \frac{\partial\dot{k}}{\partial\epsilon} = \frac{\Omega^\alpha(n+\sigma)^{1-\alpha}\gamma_0}{\alpha E[(\gamma_2-\gamma_1)\Omega^\alpha - \gamma_2(n+\sigma)^\alpha]} + \frac{\gamma_2}{E}[\frac{\Omega^\alpha\gamma_0}{(\gamma_2-\gamma_1)\Omega^\alpha - \gamma_2(n+\sigma)^\alpha}]^2 > 0,$$

$$J_{U_{22}} \equiv \frac{\partial\dot{k}}{\partial k} = -\gamma_0 < 0.$$

Note that $J_{U_{11}}$ is negative, reflecting the fact that when the level of environmental quality increases the fraction of M output used for abatement decreases, marginally decreasing as well the rate of change of ϵ. Expectedly, this pattern also appears in the mature phase. Therefore, it is important to stress that this negative and self-correcting behavior arises in a context in which the environment is defined according to anthropogenic influences. Thus, each increase in the level of ϵ will marginally decrease its rate of change. If we had supposed that the intrinsic logistic growth rate of the environment also matters for the whole dynamics of the environment, this negative effect would be compatible with a situation in which the system is to the right of the maximum sustainable yield.[10]

The conditions for the existence and uniqueness of k_U^* ensure that $J_{U_{12}} > 0$, so that a rise in the capital-labor ratio in efficiency units raises the rate of change of ϵ. The positive environmental effect on k, given by $J_{U_{21}}$, occurs through several channels. An increase in the level of environmental quality decreases the fraction of M output dedicated to abatement, thus increasing profits and, therefore, savings. Note also that a rise in ϵ will speed up the rate of change of the capital-labor ratio in efficiency units, *ceteris paribus*, via indirect effects of the corresponding decrease in $\dot{\epsilon}$. Finally, as the effect of k on $\dot{\epsilon}$ is positive, the corresponding increase in the level of environmental quality lowers the capital-labor ratio in efficiency units required to yield $\dot{k} = 0$.

The determinant of the *Jacobian* matrix in the underdevelopment phase, $|J_U|$, is given by:

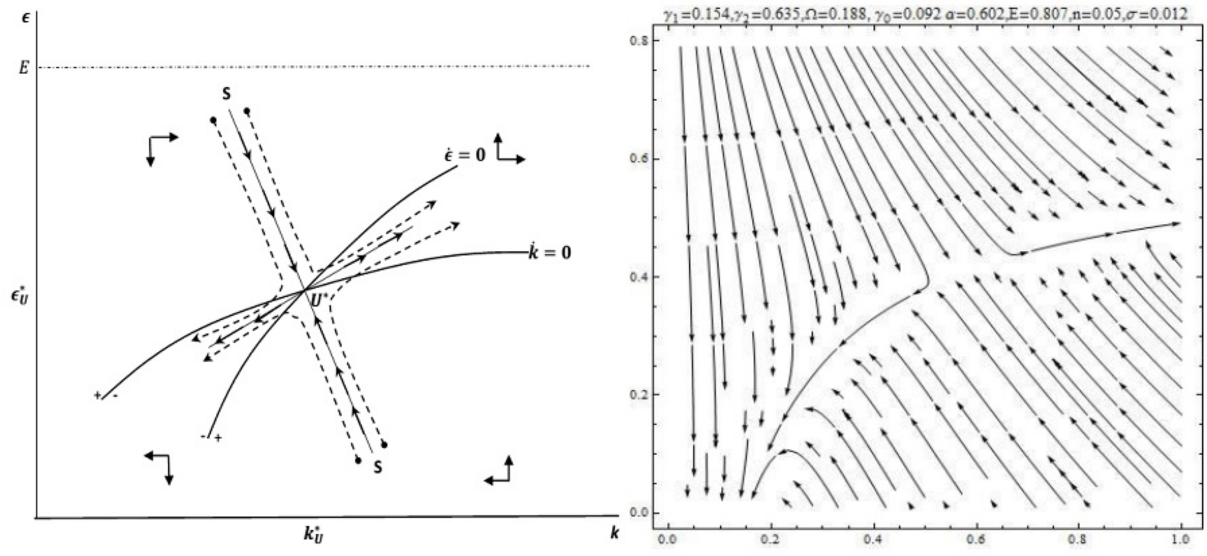
$$|J_U| = -\alpha^{-1}(n + \sigma)\Omega^{\alpha}\gamma_0 < 0, \tag{2.18}$$

which is unambiguously negative. Therefore, the equilibrium in the surplus labor phase is a saddle-point, which is represented in Figure 2.1. The phase portrait is presented in panel (a), while a vector field simulation is presented in panel (b). The simulation parameters are plausible, but arbitrary, and the conditions for existence of a real positive solution for k and ϵ are satisfied.

The axis are the respective levels for ϵ and k, with the two demarcation curves intersecting at the equilibrium point U^* and dividing the system into four distinct regions. Recall that $J_{11} < 0$, and thus, when the level of environmental quality is continuously increasing (ϵ-axis), the rate of change of ϵ undergoes a steady decrease, so that $\dot{\epsilon}$ is positive (negative) below (above) the $\dot{\epsilon} = 0$ isocline. Meanwhile, when the capital-labor ratio in efficiency units is increasing (k-axis), its rate of change is decreasing, with $\dot{k}$ being positive (negative) to the left (right) of $\dot{k} = 0$. Both curves are positively related in the neighborhood of U^*, and thus, note that even facing an infinitely elastic labor supply, capital accumulation is environment-constrained in the underdevelopment phase.[11]

[10] The maximum sustainable yield is the largest average catch that can be captured from a stock of environmental quality under existing environment conditions.

[11] These are plausible slopes of the curves; only the positive slope of both curves in the neighborhood of the unique equilibrium is important to the argument. It can be checked that, in the neighborhood of



(a) Equilibrium in the surplus labor phase. (b) Vector field simulation.

Figure 2.1: Saddle-point instability in the surplus labor phase.

Note also that the stable arm of the saddle-point, the separatrix SS, has a negative slope. All the area to the left of such stable arm constitutes what it is called here an *ecological development trap*, in which either one or both state variables experience a steady downward pressure. If the system starts to the left of SS there are no endogenous forces capable of reverting such downward pressure. This trap is called *ecological* because it arises from a pollution abatement rule enforced by an environmental authority concerned with the biophysical limits of the Planet. The economic consequences of this trap are explored in the next section.

Note that a necessary condition for the existence and uniqueness of the ecological development trap is the presence of a pollution abatement mechanism that operates when the current level of environmental quality is below its maximum attainable level. As we are interested in exploring the macrodynamic effects of such an environmental policy, we can focus our attention on the case that $\epsilon < E$, though. In fact, recall that according to (2.3), when ϵ is equal to E, the fraction of the M output allocated to abatement is null. As a result, it can be checked that the profit rate in the surplus labor phase (given in 2.9) becomes solely determined by the parameters of the production function. Meanwhile, it follows from (2.11) and (2.14) that there is no pair of economically relevant equilibrium

U^*, the $\dot{\epsilon} = 0$ isocline, whose slope is given by $-J_{11}/J_{12}$, is steeper than the $\dot{k} = 0$ isocline, whose slope is given by $-J_{21}/J_{22}$.

values in the surplus labor phase when $\epsilon = E$, given that $\dot{\epsilon}$ is unambiguously negative. And, according to (2.12) and (2.15), the same applies to $\epsilon = E$ in the mature phase.

Assuming that the economy overcomes the underdevelopment stage, let us analyze the behavior of the laws of motion of the state variables in the mature phase, when the labor supply becomes inelastic. First, computing $\dot{k} = \dot{\epsilon} = 0$, the unique economically relevant pair of equilibrium values is given by:

$$k_D{}^* = [\frac{s\alpha(\gamma_2 - \gamma_1)}{\gamma_2(n+\sigma)}]^{\frac{1}{1-\alpha}}, \tag{2.19}$$

$$\epsilon_D{}^* = [\frac{\gamma_2 - \gamma_1}{\gamma_2}]E. \tag{2.20}$$

Intuitively, the steady-state value of the level of environmental quality varies positively with the abatement effort and the maximum attainable level of environmental quality that is used as a benchmark by the government, but negatively with the catch coefficient, an immediate implication of (2.12). The same is true for the steady-state value of the capital-labor ratio in efficiency units. As in the underdevelopment equilibrium, the system is qualitatively analyzed using the criteria for local stability from the *Jacobian* matrix. Thus,

$$J_D = \begin{bmatrix} -[\frac{\gamma_2 k^{*\alpha}}{E}]\epsilon^* & [\alpha(\gamma_2(1-\epsilon^*/E) - \gamma_1)k^{*\alpha-1}]\epsilon^* \\ [\frac{s\alpha k^{*\alpha-1}}{E} + \frac{\gamma_2 k^{*\alpha}}{E}]k^* & [\frac{(\alpha-1)s\alpha k^{*\alpha-2}\epsilon^*}{E} - \alpha(\gamma_2(1-\epsilon^*/E) - \gamma_1)k^{*\alpha-1}]k^* \end{bmatrix}.$$

Substituting the corresponding equilibrium values it follows that:

$$J_{D_{11}} \equiv \frac{\partial \dot{\epsilon}}{\partial \epsilon} = -[\frac{s\alpha(\gamma_2 - \gamma_1)}{\gamma_2(n+\sigma)}]^{\frac{\alpha}{1-\alpha}(\gamma_2-\gamma_1)} < 0,$$

$$J_{D_{12}} \equiv \frac{\partial \dot{\epsilon}}{\partial k} = 0,$$

$$J_{D_{21}} \equiv \frac{\partial \dot{k}}{\partial \epsilon} = [(\frac{s\alpha(\gamma_2 - \gamma_1)}{\gamma_2(n+\sigma)})^{\frac{\alpha}{1-\alpha}} + \frac{\gamma_2}{E}(\frac{s\alpha(\gamma_2 - \gamma_1)}{\gamma_2(n+\sigma)})^{\frac{\alpha+1}{1-\alpha}}] > 0,$$

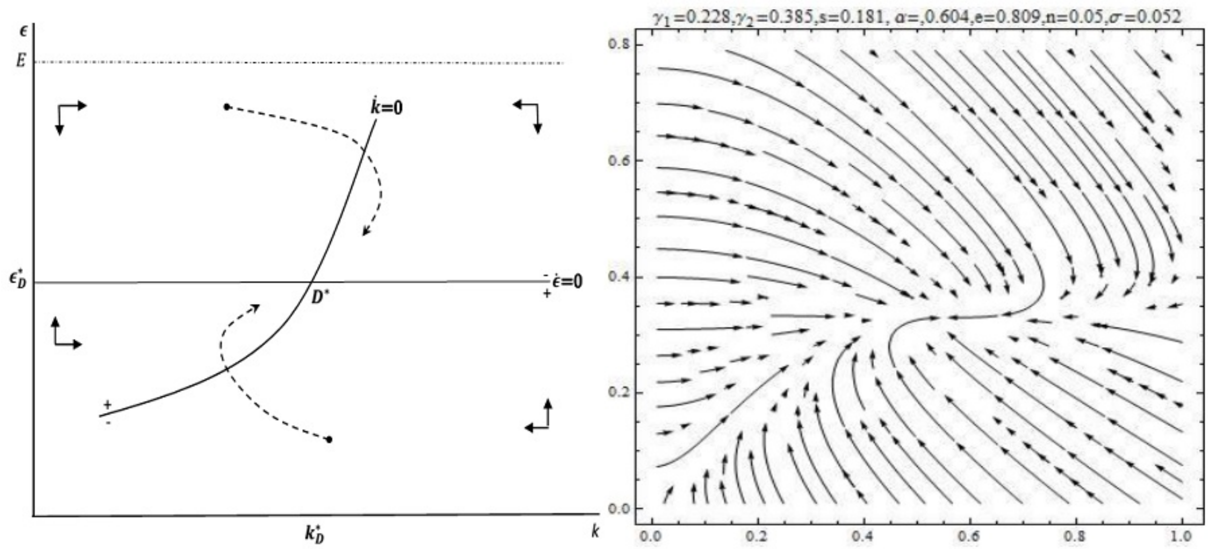
$$J_{D_{22}} \equiv \frac{\partial \dot{k}}{\partial k} = (\alpha - 1)(n+\sigma) < 0.$$

The effect of ϵ in $\dot{\epsilon}$, $J_{D_{11}}$, remains negative, but now the effect of the capital-labor ratio in efficiency units on the rate of change of the level of environmental quality in the neighborhood of the equilibrium, is null. This feature is similar to a result of the

Green Solow model, according to which the environmental rate of change is independent of the level of k. However, here the existence of decreasing marginal returns to capital is not a sufficient condition for a lowering of the amount of negative externalities on the environment. Despite $J_{D_{21}}$ is capturing the effect of decreasing marginal returns to capital, its sign remains the same, but with a smaller marginal effect than in the underdevelopment phase. The same is true for $J_{D_{22}}$, which cannot be determined directly by $J_{D_{12}}$. Note that the effect of k on its rate of change is now solely captured by the effect of k on the investment function.

As it turns out, the determinant of such *Jacobian* is unambigously positive:

$$|J_D| = (\gamma_2 - \gamma_1)[\frac{s\alpha(\gamma_2 - \gamma_1)}{\gamma_2(n+\sigma)}]^{\frac{\alpha}{1-\alpha}}(1-\alpha)(n+\sigma) > 0. \tag{2.21}$$



(a) Equilibrium in the mature phase.
(b) Vector field simulation.

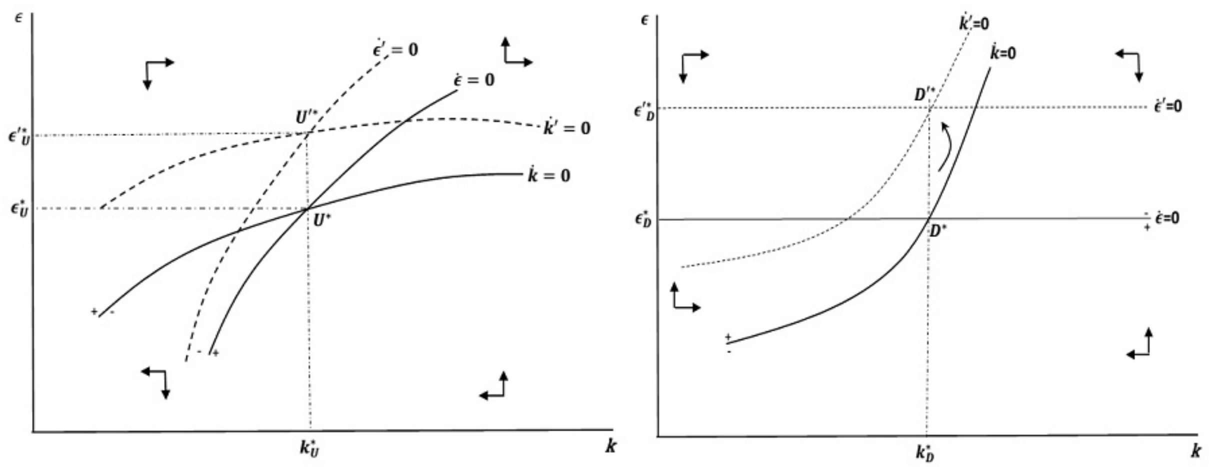
Figure 2.2: Stable equilibrium in the mature phase.

As the corresponding Trace, $Tr(J_D)$, is negative, the equilibrium in the mature phase is locally stable. Figure 2.2 presents the phase portrait (panel (a)) and a vector field simulation (panel (b)) of the system in the neighborhood of the equilibrium. As $J_{D_{11}} < 0$, when the level of environmental quality is increasing (ϵ-axis) its rate of change undergoes a steady decrease, so that $\dot{\epsilon}$ is positive (negative) below (above) the $\dot{\epsilon} = 0$ isocline. The same remains true for k. When the capital-labor ratio in efficiency units is increasing, its rate of change experience a steady decrease, so that $\dot{k}$ is positive (negative) to left (right) of the $\dot{k} = 0$ isocline.

While the $\dot{k} = 0$ isocline remains positively sloped in the neighborhood of the equilibrium, the $\dot{\epsilon} = 0$ isocline is now horizontal, given that $J_{D_{12}} = 0$. Regarding the transition to such steady state, the mathematical properties of the system and the vector field simulation reveal that the convergence is in the form of a stable improper node. Hence, convergence to equilibrium occurs with monotonically increasing or decreasing levels of environmental quality and capital-labor ratio in efficiency units, a result qualitatively analyzed in the next section.

As the dynamics of the economy are influenced by a governmental policy, let us explore how the system reacts to an exogenous change in the maximum attainable level of environmental quality used as a benchmark by the environmental authority. Assuming that the exogenous change in E is small enough, Figure 2.3 represents such comparative dynamics for the surplus labor and mature phases.

In the surplus labor phase, from (2.11) and (2.14), and the equilibrium values in (2.16) and (2.17), it follows that an initial positive shock in E moves the $\dot{\epsilon} = 0$ isocline leftward, thus positively affecting ϵ_U^*. Meanwhile, as k_U^* is not affected by E, the $\dot{k} = 0$ isocline moves in such a way that k returns to its original value. Note also that the $\dot{\epsilon} = 0$ ($\dot{k} = 0$) isocline becomes steeper (flatter) in the neighborhood of the new equilibrium. As the latter is a saddle-point, it is only by fluke that the system will converge to it. In addition, a possible rise in the size of the trap depends on the change in the slope of the separatrix SS.



(a) Change in E in the surplus labor phase.

(b) Change in E in the mature phase.

Figure 2.3: Comparative dynamics in each development phase.

In the mature phase, from (2.12) and (2.15), and the equilibrium values in (2.19) and (2.20), it follows that an exogenous increase in E also moves the economy to a higher level of environmental quality, initially positively affecting k as well. However, given (2.19), the equilibrium level of the capital-labor ratio in efficiency units is unaffected by E, so that the $\dot{k} = 0$ isocline moves in such a way to restore k_D^*. In the process of adjustment, a higher environmental quality increases labor productivity, which in turn, lowers the required level of capital *per* effective worker in the economy. Note also that the $\dot{k} = 0$ isocline becomes less steep in the neighborhood of D'^*. In both phases, the net effect of a higher value of E is to increase the steady-state level of *per capita* income of the economy, as it increases the level of environmental quality and, therefore, labor productivity in the modern sector.

2.3.1.2 Multiple equilibria analysis

This section provides a further qualitative and illustrative representation of the dynamic system by combining the unique economically relevant equilibrium in each phase of development. Indeed, there is a set of parameters for which a joint representation of Figures 2.1 and 2.2 exists. A necessary condition for this is related to the slope of each isocline in the surplus labor phase, as pointed out earlier. Note also that with $L_T = 0$, the $\dot{\epsilon} = 0$ is horizontal, so that a possible multiple equilibria configuration can be illustratively represented as in Figure 2.4.

Consider, for example, that the system starts at point A, where the level of ϵ is relatively low, and the Modern sector must dedicate a relatively high fraction of its output to abatement. Since the level of environmental quality is relatively far from its maximum attainable level and the activity of cleaning up the environment is assumed to be effective, such positive effect overcomes the negative marginal impact of ϵ on $\dot{\epsilon}$, so that the level of environmental quality increases. Meanwhile, the capital-labor ratio in efficiency units is affected in two ways. First, as the fraction of output dedicated to abatement is relatively high at low levels of ϵ, the net M output (and, therefore profits and savings) is relatively lower. Second, at relatively low levels of ϵ, the magnitude of the impact of the rise in the level of environmental quality on labor productivity is greater than the accompanying effect on savings, so that the capital-labor ratio in efficiency units falls along the trajectory started at A.

Conversely, if the economy starts at point B the level of environmental quality is

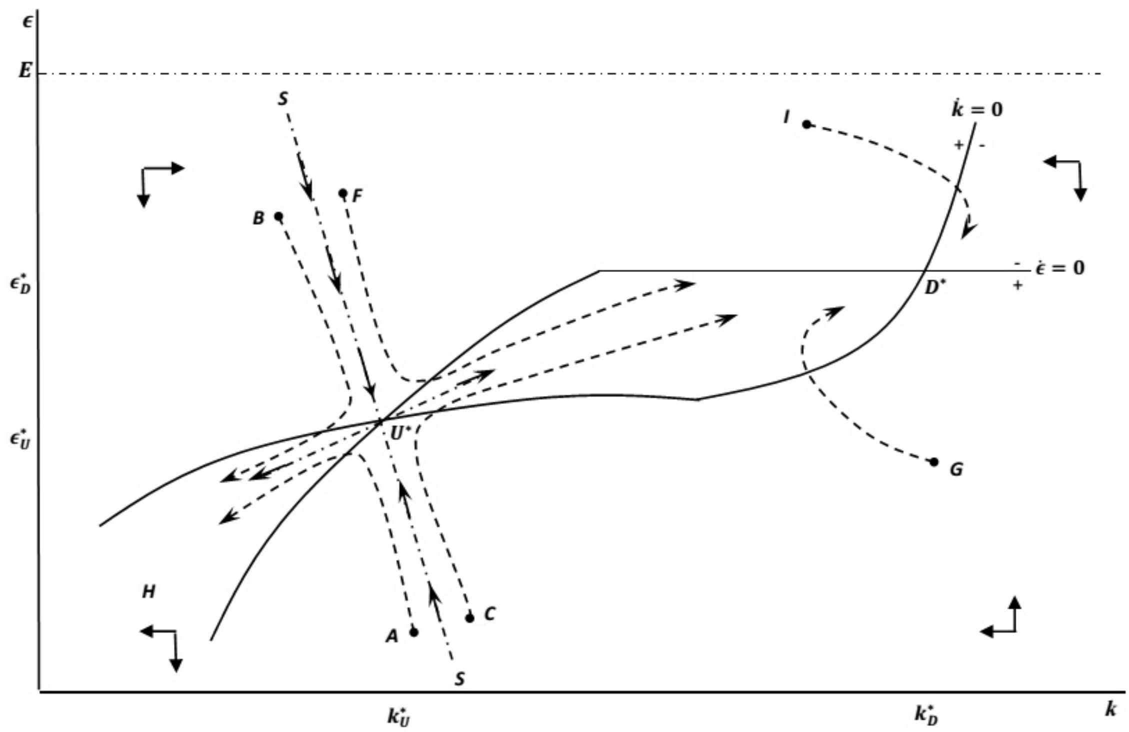


Figure 2.4: A possible configuration of multiple equilibria along the development path.

relatively high, and therefore, the fraction of the M output dedicated to abatement is relatively low. Since the level of environmental quality is relatively high, the marginal effect of ϵ on $\dot{\epsilon}$ is greater than the positive effect of k on ϵ, so that the level of ϵ experiences a steady decrease. Meanwhile, the capital-labor ratio in efficiency units is affected in two ways. First, at point B the level of pollution abatement does not compromise much the levels of profit and saving, so that capital accumulation is able to raise k. Second, the corresponding fall in ϵ requires a higher capital-labor ratio in efficiency units to yield $\dot{k} = 0$. Note that at both points, A and B, the development problem is the absence of a minimum level of environmental quality and/or capital stock *per* effective worker, which prevents the economy from being located somewhere to the right of the separatrix SS.

Consequently, the trajectories started at points A and B will eventually take the economy to a subset of the ecological development trap, the H region. Once in this region the economy experiences a cumulative decline in environmental quality and capital intensity in efficiency units, which interact in a way of a *vicious circle*. As a result, the H region illustrates the occurrence of a perverse *Kaldor-Myrdal* circular and cumulative causation mechanism of interaction between capital accumulation and environmental quality.

Note that even an economy with relatively high levels of environmental quality which adopts a pollution abatement rule may eventually fall in the Kaldor-Myrdal region of cumulative decline. This is in contrast with existing environmental macromodels, such as Brock and Taylor (2010) and Chimeli and Branden (2009). In these macromodels an economy which adopts an abatement policy will never experience a steady decline in the level of environmental quality. The result is a consequence of their sustainable growth assumptions and stability properties. In the present model, given the cumulative causation between capital accumulation and environmental quality, unfortunately this possibility arises quite naturally in the ecological development trap.

The size of the trap varies according to changes in E_U and, as a consequence, in the separatrix SS. Therefore, the main effect of the pollution abatement rule assumed here is that a developing economy, if left to the free play of its structural forces, can be trapped in the underdevelopment phase. This theoretical result illustrates the claim of many developing countries regarding the possibility of a delay in the economic development process, given the *backward effects* caused by the unequal distribution of costs and benefits of pollution abatement and, more broadly, climate change. But if the economy starts to the right of the separatrix SS, for instance at points C or F, it will converge towards maturity, even if it possibly slowly.

Once in the ecological development trap, the economy can be exogenously pushed from there to the right side of the separatrix SS by means of a standard Big Push, in the sense of Rosenstein-Rodan (1943), whose real counterpart is an international compensation mechanism. This can be accomplished through an international mechanism of transfer of financial resources that exogenously increases the level of capital intensity in efficiency units, for the same level of environmental quality.

In the present model, the theoretical possibility of a Big Push is extended to an environmental dimension. If the economy is located to the left of the separatrix SS, the ecological development trap can also be overcome by means of what we call here an Environmental Big Push, EBC. While the case for a standard Big Push is well established in the economic development literature (see, e.g., Murphy et al. 1989, and Skott and Ros 1997), this paper contributes to the environmental macroeconomics literature by providing a theoretical rationale for an Environmental Big Push. For instance, if the economy is in the H region, an EBC can push the economy from there to a point to the right of the separatrix SS, from which the convergence towards the mature equilibrium takes place, even if possibly slowly. The same possibility applies, of course, to points located out of the H region, but still in the ecological development trap, such as points A and B. Intuitively, as the level of environmental quality at point A is lower than at point B, the capital-labor ratio in efficiency units is higher in the former.

Concretely, the Environmental Big Push can be interpreted, for instance, as an exogenous transfer of green technology developed in advanced economies to the abatement activity in developing economies, which will result in exogenous improvements in the level of environmental quality in the latter. In turn, the exogenous environmental recovery will lower the fraction of the M output dedicated to abatement, which will raise the amount of savings available to finance investment. Moreover, the corresponding increase in the labor-augmenting technical change will require a lower capital-labor ratio in efficiency units to achieve similar productivity levels. Therefore, both effects are positive along the development path.

In the mature phase, unlike in Brock and Taylor (2010), our Green Lewis development model may not reproduce an EKC pattern for the environmental dynamics. For instance, if the economy starts, by a fluke, in the mature phase, say at point I, with a relatively high level of environmental quality, the system experiences a monotonic fall in ϵ towards the steady state. Consider instead that the system starts at point G, where k is relatively higher than ϵ. The level of environmental quality experiences a monotonic increase towards D^*, while k first fall and after some threshold it increases. This occurs because at G the level of environmental quality is relatively far from its maximum attainable level, and the amount of M output dedicated to abatement compromises the expansion of k. After the threshold the system enters a region of positive cumulative causation between environmental quality and capital-labor ratio in efficiency units that takes the economy to the steady state.[12]

2.4 *Conclusions*

This paper extends a Lewis dual economy development model to explore the interaction between environmental quality and economic growth, according to a modern notion of sus-

[12] When the steady state at maturity, D^*, is reached, it follows from (1) with $L_M = L$ that the level of *per capita* income is given by $M/L = \alpha(1-\phi)k^{\alpha}A\epsilon$. Therefore, as both k and ϵ are stationary in equilibrium, the steady-state growth rate of *per capita* income, as expected from the Solow (1956) nature of the mature development phase, occurs at the exogenous rate $\hat{A} = \sigma$.

tainability. Although subject to the limitations of a stylized model, the main qualitative results derived in the paper contribute to shed light on ongoing heated political discussions about whether developing countries can simultaneously stimulate economic growth and reduce negative externalities on the environment. In fact, the most recent round of these discussions was just held at the 2015 Paris Climate Conference, where over 190 developed and developing countries agreed that they need to collectively chip in by curbing greenhouse gas emissions responsible for global warming, and doing so with specific targets and performance monitoring.

When compared to the Green Solow model set forth in Brock and Taylor (2010), our Green Lewis development model yields a less auspicious prediction about the interaction between economic growth and environmental quality in developing economies. This prediction is that a developing dual economy that faces an environmental constraint to economic growth-enhancing capital accumulation by dedicating a fraction of its output to pollution abatement may not achieve the mature, developed stage. The intuition for this prediction is that such pollution abatement requirement affects capital accumulation-enhancing profitability both negatively (by reducing marketable net output) and positively (by increasing labor productivity-enhancing environmental quality). As the relative strength of these two effects depend on the prevailing levels of environmental quality and capital intensity, there emerges an ecological development trap from which a developing dual economy, if left to the free play of its structural forces, never escapes. In fact, once in such ecological development trap, a developing dual economy is either already experiencing or will eventually come to experience a Kaldor-Myrdal circular and cumulative causation process of decline in capital intensity and environmental quality.

Fortunately, however, a developing dual economy can be released from such ecological development trap and eventually, even if slowly, overcome underdevelopment not only through a standard, capital-based Big Push, in the spirit of Rosenstein-Rodan (1943), but also by means of what we call an Environmental Big Push. The latter could be based, for instance, on the adoption of international redress and compensation mechanisms in favor of developing economies. While the case for a standard Big Push is quite well established in the economic development literature, this paper is intended to contribute to the environmental macroeconomics literature by providing a sound theoretical rationale for an Environmental Big Push.

Finally, it should be emphasized that the emergence of an ecological development trap occurs in this paper in the context of a model developing economy which does not accumulate cleaner, less polluting capital. Therefore, a natural extension of this model (for which we invite the reader to stay tuned) is to incorporate the possibility of adoption of cleaner technologies. Admittedly, however, both the production and adoption of cleaner technologies are likely to be influenced, *inter alia*, by profitability considerations. More broadly, the Green Lewis development model set forth in this paper is expected to stimulate further research on other issues in ecological and environmental dynamics in developing economies. Given that global warming takes place in a global scale, it is especially appropriate to tackle these issues as they materialize in open developing economies, which may also require the use of stronger notions of sustainability.

Chapter 3

Environment, Effective Demand, and Cyclical Growth in Surplus Labor Economies

3.1 Introduction

Theoretical and empirical advances in environmental and ecological economics pose new challenges to economic growth and development theory, suggesting that limits to growth may not arise from the limited capacity of nature to provide resources, but instead from the limited ability of the planet to act as a sink for capitalist waste.[1]

Neoclassical answers to these challenges are typically optimistic, relying on the assumption that the capitalist system may still endogenously achieve a *stable sustainable* growth path. Hence, under certain conditions, the environmental constraints do not prevent the economy from achieving a full employment growth trajectory with diminishing negative impacts on the environment. In general, the argument is justified by using the controversial empirical evidence on the environmental Kuznets curve (EKC), which first appeared in Grossman and Krueger (1995).[2]

Concretely, the EKC hypothesis proposes that there is an inverted U-shaped relation between the flow of negative externalities on the environment and the levels of *per capita* income. In the first stage of development the environmental degradation grows quickly because financial resources to invest in pollution abatement are relatively low and capital accumulation is at the forefront.. With this ongoing development process, there is an

[1] See, for example, Brock and Taylor (2004) and Foley (2012) for some reflections on these new challenges (or dilemmas).

[2] Stokey (1998) and Brock and Taylor (2010), for instance, formulated models in which the EKC standard prediction plays an important role in generating such a sustainable growth path in mature economies.

income threshold above which the economy starts to invest in pollution abatement and mitigation so that eventually, growth reduces the negative environmental impact of economic activity. In the words of Stokey (1998, p.1): "while the early stages of economic growth cause the problem, later ones bring the remedy."

Several objections can be raised against the theoretical foundations of the EKC. Mostly, its concept is dependent on a model of the economy in which there is no feedback from the environmental quality to economic growth, meaning that in the absence of an environmental regulation, growth can expand at no environmental cost. One might wonder whether the assumption of zero environmental cost is so general as supposed. The answer is no. It is difficult to imagine, for instance, that such assumption remains true when we consider that the environmental degradation problem takes place on a global scale in which trade has, by no means, a neutral effect (Stern, 2004). Some may choose, of course, to transfer this global cost to future generations, but in the face of the climate change problem, this line of argument has not been helpful.[3]

The heart of the critique is simply that the neoclassical optimism is implicitly based on the assumption that countries in the early stages of development have relatively high levels of environmental quality and may sacrifice of these levels in order to grow quickly. However, in some low-income developing economies (including much of Asia and Africa), such a growth strategy can actually result in an unsustainable increase in environmental degradation before the maximum range of pollution illustrated by the EKC is reached (Dasgupta et al., 2002). This is so precisely because they have relatively low levels of environmental quality.

The main feature of these developing economies is the occurrence of *environment adjustment costs* that are already binding in the short run. Any expansion of economic activity comes with even more negative impacts on the environment which, if strong enough, may compromise output expansion in the capitalist sector. It is the corresponding lowering in economic growth toward the medium run that reduces the negative pressures on the environment so that, for environmentalists, the existence of developing countries with re-

[3] The feedback effect from environmental quality to economic growth also has serious implications for the assumption of of strict exogeneity in econometrics models seeking to empirically test the EKC. This paper, however, scrutinizes the voluminous literature on the EKC. See Carson (2010) and Stern (2015) empirical analyses of the EKC.

latively low levels of environmental quality offers empirical evidence against the arguments based on the EKC and the prediction of a well-behaved growth trajectory.[4]

International development agencies have highlighted empirical evidence that illustrates such a claim for developing countries such as Rwanda, were the cost of land degradation has been negatively affecting gross domestic product (GDP).[5] Particularly, Rwanda is under perverse Malthusian dynamics: an increase in economic growth stimulates agricultural consumption, which given the rudimentary techniques adopted by low-skilled workers, accelerates soil degradation and reduces productivity, in turn lowering GDP. Furthermore, in several low-income regions of China, industrial production has led to atmospheric pollution, increasing the rate of health and occupational problems with direct consequences on labor productivity. In turn, less productive workers exert downward pressure on industrial production and growth. Moreover, both cases illustrates the occurrence of different types of environmental adjustment costs; this operates as a feedback mechanism from environmental quality to output expansion.

Relatively much less attention has been given to the theoretical macroeconomic aspects of the problem. Bulte and van Soest (2001), as a notable exception, formalize a model in which production and consumption patterns of rural households in developing countries are the main source of environmental degradation. Depending on the indicator that is used to represent the environmental externality, for reasonable parameters, the model demonstrates that a reverse causal behavior may arise as a particular case of the EKC dynamics. Its focus is on the generation of an extended EKC and not on the macroeconomic consequences for such an extension for developing countries; thus, many issues remain.

A major question in this context is how these developing countries, or some of them, are likely to behave in a trajectory of this type as far as their macroeconomy is concerned. A first step in addressing such concern is to set forth a formal model that explores the macroeconomic implications, in one of its several relevant aspects, of such a *conflictive* relation between environmental quality and economic growth in these surplus labor low-income economies. The main purpose of this paper is to develop such a model.

Far from full employment, these economies are characterized by hidden unemployment

[4] In the long run effect, of course, this will depend on how absolute poverty responds to slower economic growth.

[5] See, for example, Downing et al. (2009) and part of the *environment–poverty literature*: Bôjo et al. (2001), Dasgupta et al. (2005).

and the existence of a relatively large capitalist sector coexisting with a larger subsistence sector. In this context, effective demand plays an important role in generating a long run path, which according to Harrod (1939) is likely to be unstable. In the medium run, in addition to driving the output expansion, effective demand generates negative externalities on the environment that reduce the level of environmental quality. In turn, such an effect raises the environmental adjustment costs of firms, thus exerting a downward pressure on economic growth. Hence, instead of suggesting a stable sustainable growth path, as proposed by most neoclassical constructions, this aspect of the relation between environmental quality and economic growth may result in a medium run *vicious circle*, in which the level of environmental quality operates as a potential taming mechanism for the *Harrodian* instability in such developing economies.

Such theoretical description requires that we shift the focus from a well-behaved trajectory of long run stable growth to the description of endogenous cyclical fluctuations. A theoretical framework that quite naturally accommodates this possibility is the *Harrodian* one, in which effective demand plays a pivotal role. However, cycles arises in a standard version of this model only for mature economies, in which capital accumulation endogenously affects the structure of the labor market. In the present surplus labor case, however, the theoretical explanatory power of the *Harrodian* framework is extendend to include environmental considerations, with which another source of cyclical growth arises as a new accommodation mechanism of instability.

Ironically, the post-Keynesian literature is not immune to the criticism that it has largely ignored sustainable development issues. However, the tide is changing, and the present paper is related to a few attempts to model environmental and ecological issues in a post-Keynesian framework, such as Fontana and Sawyer (2016) and Taylor et al. (2016). The main distinguishing feature and contribution of the present simple model is that it provides a plausible explanation for a possible new source of cyclical growth in such surplus labor economies. At the very least, the model set forth herein provides insights that should be considered in an evaluation of the conflictive relation between environmental quality and economic growth in low-income developing economies with relatively low levels of environmental quality.

The remainder of this paper is organized as follows: Section 3.2 extends a standard *Harrodian* model to include an environmental dimension, thus exploring the relationship between effective demand and the environmental adjustment costs. The balanced growth and the (in)stability properties of the model are analyzed in Section 3.3, in which an economic interpretation of the main results is presented. Finally, the main conclusions derived along the way are summarized in Section 3.4.

3.2 The model

Consider a surplus labor developing economy with relatively low levels of environmental quality that is closed and has no fiscal activities. Such a relatively low level of environmental quality is caused by a local effect (to be described latter). The dualism is represented by the coexistence of capitalist and backward sectors, the latter being a repository of hidden unemployment. The capitalist sector produces according to a production function with fixed coefficients that combines capital, K, and labor, L, in which it is supposed that there is no labor hoarding and the excess of capital capacity is the normal state of affairs. These assumptions imply that the output, X, is given by the following:

$$X = xL \leq \rho^{max} K, \tag{3.1}$$

where x is labor productivity and ρ^{max} is capital productivity at the full capacity level. Since capital stock is subject to lag adjustments, firms may want to maintain excess of capacity to deter new entry and to respond to fluctuations in demand (Steindl, 1952).

One of the crucial aspects of the *Harrodian* benchmark is related to the investment sensitivity to capital capacity utilization in the short and long run, the equality of desired (ρ^*), and actual output–capital ratio (ρ) in the steady state. Hence, a standard *Harrodian* investment function relates the rate of change in the rate of accumulation, $d\dot{K}/dt$, to the difference between the actual output–capital ratio and the desired ratio (Skott, 2010).[6] Hence,

$$\frac{d}{dt}\hat{K} = \lambda(\rho - \rho^*), \ \lambda > 0. \tag{3.2}$$

Following the classical economists and the Cambridge (UK) tradition, it is supposed that workers as a class spend all of their income, whereas capitalists save a constant

[6] This function is a continuous approximation for a discrete investment function that only considers the output–capital ratio as affecting investment for the purpose of simplicity. See Skott (2010).

fraction, s, of gross profits, Π (Kaldor, 1966):

$$S = s\Pi. \tag{3.3}$$

Regarding gross investment, a standard specification is given by the following:

$$I = \frac{dK}{dt} + \delta K, \tag{3.4}$$

in which δ is an exogenous depreciation rate. The capital stock, the rate of capital accumulation, and the output are predetermined in the ultra-short run. These past production decisions are governed by demand expectations that sometimes are not fulfilled. Unlike most Keynesian and Kaleckian approaches, it is supposed that output cannot adjust instantaneously to a demand shock. The Keynesian equilibrium condition, $S = I$, is thus brought about by changes in prices (in both directions). Therefore, it is supposed that firms may respond to unexpected shocks in aggregate demand by adjusting prices, and as profit share, π, is determined by a mark-up pricing equation, profits increase. This approach also finds support on the *Treatise on Money* of Keynes (1976).[7]

The causality channel is as follows: the level of output is predetermined in the ultra short run, and a rise in demand leads to an increase in the price of output. Money wages are fixed since there is no perfect foresight and instantaneous feedback from prices to money–wages rates. Thus, real wages and the profit share respond to unanticipated movements in prices, and a positive demand shock increases the profit share. The investment and savings equilibrium condition for a given profit share generates the following solution for the output–capital ratio, ρ, in the ultra short run:

$$\rho = \frac{\hat{K} + \delta}{s\pi}. \tag{3.5}$$

Therefore, the *Keynesian* equilibrium condition, $S = I$, defines a sort of Marshallian ultra-short run equilibrium: a market clearing price vector is defined, but it may give firms an incentive to change their production directly after this.

When the system moves over time using (3.5) in (3.2) the rate of change of capital accumulation becomes the following:

[7] As argued by Skott (2015), perfect flexible prices are not so problematic an assumption as imagined, since in his approach, cyclical growth can arise with or without flexible prices.

$$\frac{d}{dt}\hat{K} = \lambda(\frac{\hat{K} + \delta}{s\pi} - \rho^*), \tag{3.6}$$

which in equilibrium, defines the *warranted* growth rate, g_w:

$$\hat{K}^* = s\pi\rho^* - \delta = g_w. \tag{3.7}$$

This solution for the rate of accumulation at the stationary level is *warranted* because on average, firms achieve precisely the desired rate of utilization in the long run, ρ^*, a rational expectation equilibrium (Nakatani and Skott, 2007), as can be seen by using (3.7) in (3.5). However, it gives rise to the well know instability mechanism described in Harrod (1939) as well as the likely inequality between g_w and the natural growth rate, which Harrod sees as an intrinsic characteristic of capitalist societies.

Skott (1989a) reconciles the warranted and natural growth rate without leaving aside the endogenous fluctuations of capitalist economies. This mechanism operates through the interaction between effective demand and the employment rate, which evolves in time according to *predator–prey* dynamics. However, in a surplus labor economy, the employment rate carries little information to the capitalist sector. As a result, the labor market may not change endogenously in response to variations in capital accumulation. In this case, the cyclical pattern of *Harrodian* models may not arise unless another containment mechanism is in operation. As described in what follows, the environmental quality can serve as a channel for such a mechanism.

3.2.1 The output expansion function and the environment dynamics

The *Harrodian* framework supposes that firms respond to shocks in aggregate demand in the ultra short run via price adjustments because production is subject to adjustment costs and takes place after some time. To accommodate such an assumption, it is supposed that profit-maximizing firms choose the rate of expansion of production instead of the level of output, which balance the costs and economic benefits of moving toward a desired level of utilization. This rate of expansion is selected subject to effective demand, technical, and cost constraints.

In the present surplus labor case, the demand signs comes from the profit share and the cost signs from the level of environmental quality, ϵ. To model the feedback effect from the level of environmental quality to economic growth, it is supposed that a relatively lower level of environmental quality is associated with a relatively higher amount of environmental adjustment costs of production. The effect will be modeled through its negative effects on the productivity of the labor force. Hence, the *Harrodian* rate of growth of production is algebraically defined as follows:

$$\hat{X} = h(\pi, \epsilon),\ \ h_\pi, h_\epsilon > 0, \tag{3.8}$$

which supposes that the environmental adjustment costs, whose effect is captured by the level of environmental quality, are convex; thus $\hat{X}$ can be modeled in continuous time. The model, therefore, leaves aside the possibility that relatively strong changes in the environment can cause discrete changes in the environmental adjustment costs (non-convexities). However, in a scenario of climate change, this discrete effects may be important for the cost structure of firms, a possibility from which we abstract.

In a *Harrodian* framework a certain degree of capitalists' inability to respond to demand shock is supposed, but in the present case, this inability also assumes an environmental dimension. The inability of instantly adjusting to a change in the environmental quality arises because the economic representative agent does not perfectly observe his or her negative externalities on the environment (Kelly et al., 2005). An agent in a developing country with a relatively low level of environmental quality only slowly realizes that the environment has changed.

However, if a negative change in environmental quality is persistent, firms know that it lowers labor productivity, given the negative effects of pollution on the health and cognitive abilities of factory workers. To counterbalance the reduction in the level of environmental quality, firms increase investments in occupational health and training of the labor force in the exact amount to maintain labor productivity unchanged, which I shall refer to as environmental adjustment costs. It is supposed that firms always achieve such a goal at any level of ϵ. Note that there is an inverse relationship between the level of environmental quality and the environmental adjustment costs; thus we can model the output expansion dynamics as described in (3.8).

The recognition that the level of environmental quality can affect human health is not new, but the economic research only recently expanded the focus of analysis beyond direct health outcomes. Many health effects can affect human capital and labor productivity both in the short run (Currie and Stabile, 2006) and the long run (Cunha and Heckman, 2007). A recent and growing body of literature has begun to make this link more explicit, providing empirical evidence that justifies this functional relation between environmental quality (or pollution, as the inverse) and labor productivity as well as the cognitive outcomes.[8]

Analyzing the effects of negative changes in ozone concentration, Graff Zivin and Neidell (2012) found robust evidence that ozone levels well below the federal air quality standards have a significant negative impact on labor productivity. The magnitude of the impact is large, since they found that a 10 ppb (parts per billion) decrease in ozone concentration increases labor productivity by 5.5 percent. The authors argued that investment in environmental protection could be seen as an investment in human capital as well. Similarly, Chang et al. (2014) estimated the effect of outdoor air pollution on the labor productivity of indoor workers in a pear-packing factory. They also found that an increase in particulate matter less than 2.5 micrometers in diameter (PM2.5) of a harmful pollutant outdoors, which easily penetrates indoor settings, lead to a statistically and economically significant decrease in packing speeds inside the factory.

The level of environmental quality modeled as environmental adjustment costs is also compatible with short-run adjustments in the *Harrodian* perspective. Graff Zivin et al. (2015) provided the first estimates of the potential impact of climate change on human capital, focusing on the impacts from both short-run weather and long-run climate. Exploiting a longitudinal structure of the $NLSY79$ and random fluctuations in weather across interviews, they identified the effect of temperature in models with child-specific fixed effects, finding that short-run changes in temperature lead to statistically significant decreases in cognitive performance in mathematics.[9] In contrast, a long-run analysis revealed no statistically significant relationship between climate and human capital. According to the authors, this finding is consistent with the notion that adaptation, particularly compensatory behavior, plays a significant role in limiting the long run impacts from short run weather shocks. In the present approach, it may be consistent that in the long run, firms move to a desired level of utilization via adaptation, even when facing environmental constraints on the labor force.

[8] See Graff Zivin and Neidell (2013) for a summary of this literature.

[9] The NLSY79 cohort is a longitudinal project that follows the lives of a sample of American youth born between 1957 and 1964.

One may ask, however, if these environmental adjustment costs are economically relevant. In the climate change literature, this is a controversial point. In fact, most old quantitative estimates of the cost of environmental damages in mature economies are modest. This is a different cost perspective taked by the empirical evidence reviewed by Graff Zivin and Neidell (2013), which argue that most recent estimates inf the literature have found economically relevant parameters related to environmental damages. Intuitively, for low-income developing economies with relatively low levels of environmental quality, however, a conclusion that such a cost is relatively small seems misguided. In the real world, of course, the way in which the signals of environmental quality are captured by the capitalist sector are diverse and difficult to generalize; thus, I focus on the effects on labor productivity following the recent and robust empirical evidence that is economically relevant (Graff Zivin and Neidell, 2013).

In contrast, the level of environmental quality changes endogenously according to the pollution that the capitalist sector releases into the environment. This is captured by a local scale effect.[10] Hence, the flow of pollution is defined according to the following::

$$\Omega = \vartheta(X),\ \vartheta > 0, \tag{3.9}$$

where the higher the scale of the economy, the lower the level of environmental quality. The level of environmental quality is given in the short run, but it has an exogenously given natural capacity of regeneration over time, β.

The level of environmental quality grows according to a logistic function, which is perhaps the simplest plausible functional form for biological growth in a constrained environment, $G(\epsilon)$, defined as follows:

$$G(\epsilon) = \beta(E - \epsilon)\epsilon, \tag{3.10}$$

where E, the maximum carrying capacity point, is the maximum possible level of environmental quality, so that when $\epsilon = E$, further growth cannot occur, $G(\epsilon) = 0$. It is supposed that the proportional rate of change of environmental quality is negatively affected by the

[10] From an empirical perspective, there are three ways through which an economy generates pollution: scale, composition, and technical effects. The present model concentrates only on scale effects since it is a one sector model that abstracts from the occurrence of technical change.

growth rate of the flow of pollution, thus having an inverse relationship with the output expansion function:

$$\hat{\epsilon} = \beta(E - \epsilon) - \omega[h(\pi, \epsilon)], \tag{3.11}$$

where ω measures the intensity of the negative impact of the output expansion on the environment. A stationary solution for ϵ, thus, requires the balance between effective demand and its polluting dynamics with the natural capacity of regeneration of the environment.

For the present purposes, it is not convenient to link this description of the environmental quality to climate change. In all of the analyses that follow, the negative externalities from the capitalist sector are local, as in many models in the related literature.[11] Thus, it is more convenient to think of the environmental quality as the ecological complex consisting of the forest, soil, water, and air quality so that "the environment" assumes this particular meaning. A substantive assumption, however, is necessary. The level of environmental quality must respond in a sufficiently positive amount to the negative oscillation in the production in order to capture the diminishing pressures on the environmental adjustment costs. Therefore, all of the environmental externalities are suitable to this medium run perspective of the model since some negative impacts on the environment are permanent or take a very long time for significant regeneration, thus exerting a continuous negative effect on the labor force.[12]

Before analyzing the mathematical properties of the model, it may be useful to compare it with other attempts to model similar environmental and ecological dynamics in macromodels, especially the attempt to model how environmental quality affects labor productivity and economic growth, growth, with which the present model shares a lot of inspiration.

Oliveira and Lima (2015), using a Lewis dual economy framework, specify a labor-augmenting process of technical change that is influenced by the level of environmental quality in a Cobb–Douglas technology. They show that even in a very optimistic EKC context, pollution abatement policies without exogenous compensation mechanisms may

[11] For the present purposes, an open macroeconomic model of climate change will just increase the negative environmental effect. See, for example, Copland and Taylor (2005) for some open macromodels along neoclassical lines. A recent and elegant structuralist formalization of open ecological macroeconomic issues can be found in Razmi (2015).

[12] Industrial toxic pollution is typically procyclical.

result in an ecological development trap, from which a developing economy, if left to the free play of its structural forces, may never escape. However, such a result is independent of the labor-augmenting effect. The main source of environmental cost comes from a profitability reducing pollution abatement rule, which is endogenous to the level of environmental quality. Meanwhile, the authors ignore effective demand issues as affecting economic growth. Here, I consider that even without environmental regulation, a similar conflictive behavior may arise in a context in which the role of effective demand in generating an unstable warranted growth path is explicitly taken into account.

In Taylor et al. (2016), a large set of variables affect labor productivity. In particular, they claim that greenhouse gas emissions may decrease labor productivity since they also cuts "profitability and destroys the stock of capital". However, this channel from which environmental quality (or pollution) affects labor productivity is not explained in detail. They also establish an interesting link between energy and productivity through which important growth and distribution outcomes are analyzed. In contrast, the present model adopts a more parsimonious specification, examining the role of environmental adjustment costs, which arise from the action of firms to prevent the loss in labor productivity through health shocks, in generating cyclical growth.

3.3 Demand-driven economic growth and (in)stability

At any moment in time, the rate of output, X, the capital stock, K, the level of environmental quality, ϵ, and the output–capital ratio, ρ, are given. The equilibrium in the goods market determines income distribution, π. As a consequence, the output expansion and the investment function determine the growth rate of output and capital accumulation, which in turn will determine the level of environmental quality.

In a simple *Harrodian* benchmark, the output–capital ratio is constant and equal to ρ^* along a steady-state path. As argued before, a key element is the distinction between a weak short-run and strong long-run sensitivity of investment to variations in aggregate demand. With capacity utilization being a state variable, this distinction is captured by a static relation between the accumulation rate and capacity utilization (Skott, 2010):

$$\hat{K} = \varphi(\rho), \tag{3.12}$$

in which φ measures the relationship between accumulation and the output–capital ratio.

As the profit share is determined by the equilibrium condition for the goods market, we can use (3.12) in (3.5) to determine the long run relation given by the following equation:

$$\pi = \frac{\varphi(\rho) + \delta}{s\rho} = \mu(\rho), \tag{3.13}$$

in which the strong long run sensitivity of the rate accumulation to changes in output–capital ratio implies that $\mu' > 0$.

Using (3.8), (3.11), and (3.12) the two-dimensional system can be algebraically written as follows:

$$\hat{\rho} = \hat{X} - \hat{K} = h(\mu(\rho), \epsilon) - \varphi(\rho), \tag{3.14}$$

$$\hat{\epsilon} = \beta(E - \epsilon) - \omega[h(\mu(\rho), \epsilon)]. \tag{3.15}$$

The system given by (3.14) and (3.15) will have a steady state solution if $\dot{\epsilon} \equiv d\epsilon/dt$ and $\dot{\rho} \equiv d\rho/dt$ are simultaneously equal to zero so that reconciliation between the warranted and natural growth rate is environment-constrained in this surplus labor economy. This simple model exhibits four steady states: three corner solutions of $(\epsilon^*, \rho^*) = (0,0), (E,0), (0, \rho^{*'})$ and one interior solution, which is the unique pair of equilibrium that is economically relevant and will be explored in the (in)stability analysis that follows.

Figure 3.1 illustrates a possible steady-state configuration using the output expansion (3.8) and the logistic growth function of environmental quality (3.10) in Panel (a). The equilibrium level of environmental quality, ϵ^*, implies that $\dot{X} = h(\pi, \epsilon^*)X$ just matches the growth of environmental quality, $G(\epsilon)$, at $\epsilon = \epsilon^*$. Hence, ϵ^* is an equilibrium point if we explicitly treat ρ as fixed. However, ρ varies over time, which is pictured in Panel (b) in Figure 3.1. The illustrative discussion of Figure 3.1 implicitly assumes so far that the effects of ϵ on the output expansion function is nonlinear but focusing only on the relevant, positive domain.

The nonlinearity of the output expansion illustrates that for a relatively high level of environmental quality, the growth rate of output is relatively insensitive. The same remains true for the growth rate of the output–capital ratio.

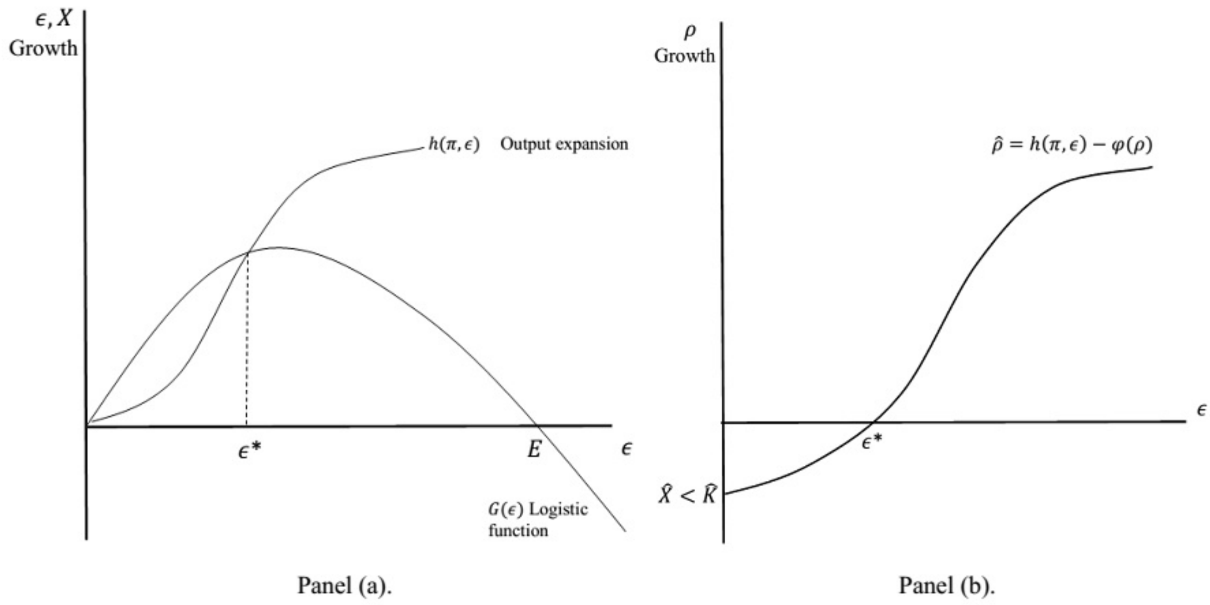


Figure 3.1: Environmental quality, effective demand, and economic growth.

In order to compute the interior solution of the dynamical system given by (3.14) and (3.15), I set $\hat{\epsilon} = 0$ to obtain the following:

$$\frac{\beta(E-\epsilon)}{\omega} = h(\mu(\rho), \epsilon) \tag{3.16}$$

and substituting (3.16) in (3.14) with $\hat{\rho} = 0$, the following is true:

$$\varphi(\rho) = \frac{\beta(E-\epsilon)}{\omega}. \tag{3.17}$$

Isolating ρ under the equilibrium for the profit share in the long run, (3.13), we can use the corresponding result in (3.16) to obtain the equilibrium level of environmental quality, ϵ^*. Intuitively, such a level will be in the relevant positive domain if and only if the impact of economic activity on the environment is not too high. Such a corresponding solution for (3.16) can be substituted in (3.17) to obtain the unique relevant positive equilibrium value for the output–capital ratio.

The system (3.14)–(3.15) is qualitatively analyzed around the interior steady-state solution, in which the local stability properties are determined by the corresponding *Jacobian* matrix:

$$J = \begin{bmatrix} (h_\pi \mu' - \varphi')\rho & h_\epsilon \rho \\ -\omega h_\pi \mu' \epsilon & -(\beta+\omega) h_\epsilon \epsilon \end{bmatrix}.$$

In a standard *Harrodian* model, J_{11}, the effect of the output–capital ratio on $\dot{\rho}$, is positive, as the short-run macroeconomic multiplier ensures that $d\hat{X}/\hat{K} - 1 > 0$ (under the supposition that adjustment variations in output are fast relative to any movement in the capital stock) (see Skott 1989b for a detailed discussion). In the present model, the marginal effect of the level of environmental quality on $\dot{p}$, J_{12}, is positive. The rise in the level of environmental quality raises the growth rate of output since it reduces the environmental adjustments costs related to health and training expenditures to maintain labor productivity unchanged.

In turn, an increase in the output–capital ratio lowers the growth of rate of the level of environmental quality in the economy, $J_{21} < 0$, given its positive effects on the output expansion. J_{22} measures the negative impact that ϵ has on its rate of change, which is negative, as expected, in a logistic specification for the level of environmental quality when the effects of output are given.

As a consequence, the corresponding determinant and the trace are respectively given by the following:

$$Det(J) = \varphi' \beta \rho \epsilon > 0, \tag{3.18}$$

$$Tr(J) = (h_\pi \mu' - \varphi')\rho - (\beta + \omega) h_\epsilon \epsilon. \tag{3.19}$$

The determinant is unambiguously positive; however, the trace is ambiguous. A result with a negative trace (a locally asymptotically stable equilibrium point) will require strong negative feedback effects from environmental quality to its rate of change, J_{22}, in a sufficient amount that yields $h_\pi \ \mu' \rho < \varphi' \rho + (\beta + \omega)_\epsilon \epsilon$.

A positive trace (a locally asymptotically unstable (or repellor) equilibrium point) requires that J_{11} be greater than J_{22}. In such a case, as the determinant is positive, the neighborhood of the equilibrium may be characterized by a *limit cycle*. However, what are the global stability properties of the system (3.14)–(3.15)? To examine the global behavior of the system, and the possible existence of a limit cycle as a global property, a sufficient condition is to show that there is a closed and bounded subset of the positive domain with the property that if the initial value of the state variables start in this region then the trajectories represented by (3.14) and (3.15) will not exit this subset (a trapping region). If such a condition is satisfied, the Poincaré–Bendixson theorem guarantees that all trajectories in the subset will converge to a closed orbit, thus exhibiting perceptual cyclical behavior (Lima, 2004).

First, note that by the Bendixon criteria we cannot rule out that $Div\vec{F} \equiv \frac{d\rho}{dt} + \frac{d\epsilon}{dt} = 0$; thus we cannot rule out the non-existence of a closed orbit within the economically relevant domain and thus the non-existence of a limit cycle. Figure 3.2 shows a qualitative illustration of a possible trapping region in the state space of the dynamical system represented by (3.14) and (3.15) with a positive trace.

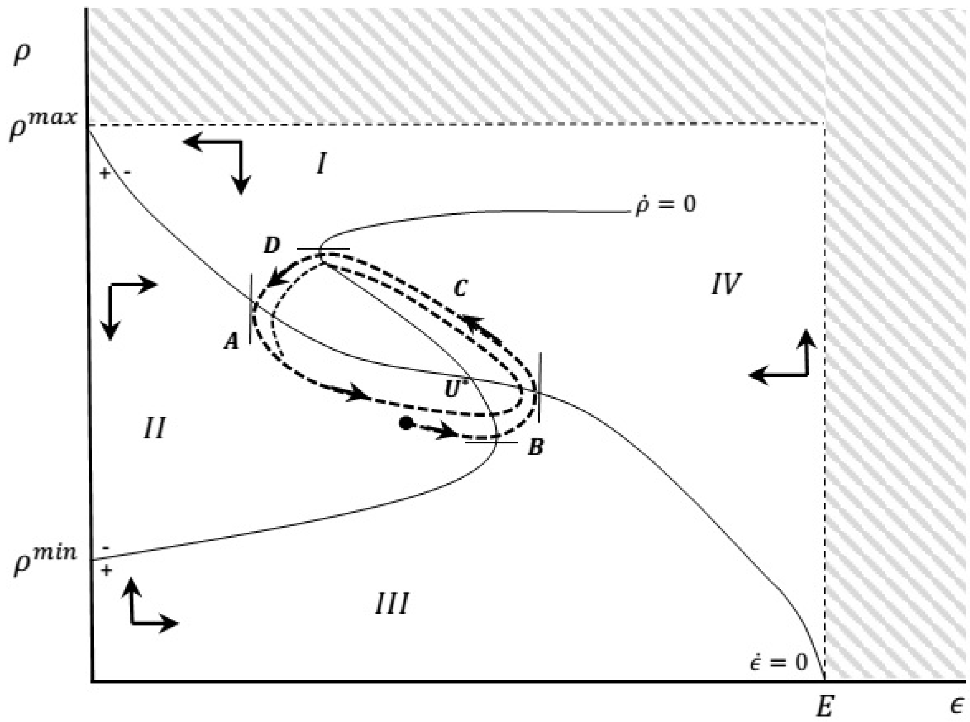


Figure 3.2: A possible limit cycle in the surplus labor economy.

The rationale for the construction of this trapping region is as follow. Both isoclines, $\dot{\epsilon} = 0$, and $\dot{\rho} = 0$, are negatively sloped in the neighborhood of the unique equilibrium point, U^*. The $\dot{\epsilon} = 0$ isocline is negatively sloped in the positive domain. Around U^*, as $J_{22} < 0$, when the level of environmental quality is increasing, its rate of change is steadily decreasing so that the signals of $\dot{\epsilon}$ are positive (negative) below (above) the $\dot{\epsilon} = 0$ isocline. In turn, in the neighborhood of U^*, a rise in the output–capital ratio raises its rate of change so that $\dot{\rho}$ is increasing (decreasing) above (below) $\dot{\rho} = 0$. The full configuration of $\dot{\rho} = 0$ is depicted under the following assumptions: (i) there is a minimum level of output–capital ratio in the economy, ρ_{min}, at which I suppose that $\hat{Y} > \hat{K}$; (ii) for high values of ρ, $\hat{Y} < \hat{K}$; and (iii) for high levels of environmental quality, the locus, $\dot{\rho} = 0$, is flatter.

The first assumption is important to generate a floor for the cyclical fluctuations, which are now bounded from below, and to guarantee that for relatively low levels of output–capital ratio, ρ is increasing. This is consistent with the notion that firms target a minimum margin of profits to produce so that below this point, the output–capital ratio is increasing to maintain at least the minimum profit share. The second assumption is important to ensure that the fixed–coefficient assumption, $\rho < \rho^{max}$, holds for relatively high values of ρ (that is, far from the neighborhood of U^*). The third assumption is related to the lower sensitivity of output–capital ration for relatively high levels of environmental quality since at such a level the influence of the environmental adjustments costs on the output expansion is lower.

To check the consistency of the bounded subset, note that if these assumptions are satisfied, at *very* large values of output–capital ratio, $\dot{\rho}$ is decreasing. Note also that the system is naturally bounded from above by the maximum carrying capacity, E, so that at *very* large values of ϵ, the rate of change of the level of environmental quality is also decreasing. Both are represented by the silver area. In addition, for *very* large values of ρ and ϵ (the northeast region in Figure 3.2), the sensitivity of the output expansion to a change in the output-capital ratio (capacity utilization) and the level of environmental quality is zero; thus $\dot{\rho} = -\varphi(\rho)$ and $\dot{\epsilon} = -\infty$ – so that $d\rho/d\epsilon \approx 0$. Such conditions form a possible trapping region that do not contain an equilibrium point (except in the closed orbit), so that the Poincaré–Bendixon theorem guarantees the existence of a limit cycle within such a region.

As the stability of the unique economically relevant equilibrium solution cannot be ruled out, Figure 3.3 depicts this possibility. The main difference between this and the previous analysis is that instead of exhibiting perpetual oscillatory behavior, the economy moves cyclically to the stable focus, $U^{*'}$, which is likely much different from U^* in Figure 3.2. Whether this equilibrium is higher or lower that the one represented in Figure 3.1, this is of course something which depends on the parameter values.

One may wonder in what situations the response of the rate of change of the level of environmental quality to changes in ϵ is strong enough to produce such a result. It depends on the type of negative externality in each low-income developing economy. It

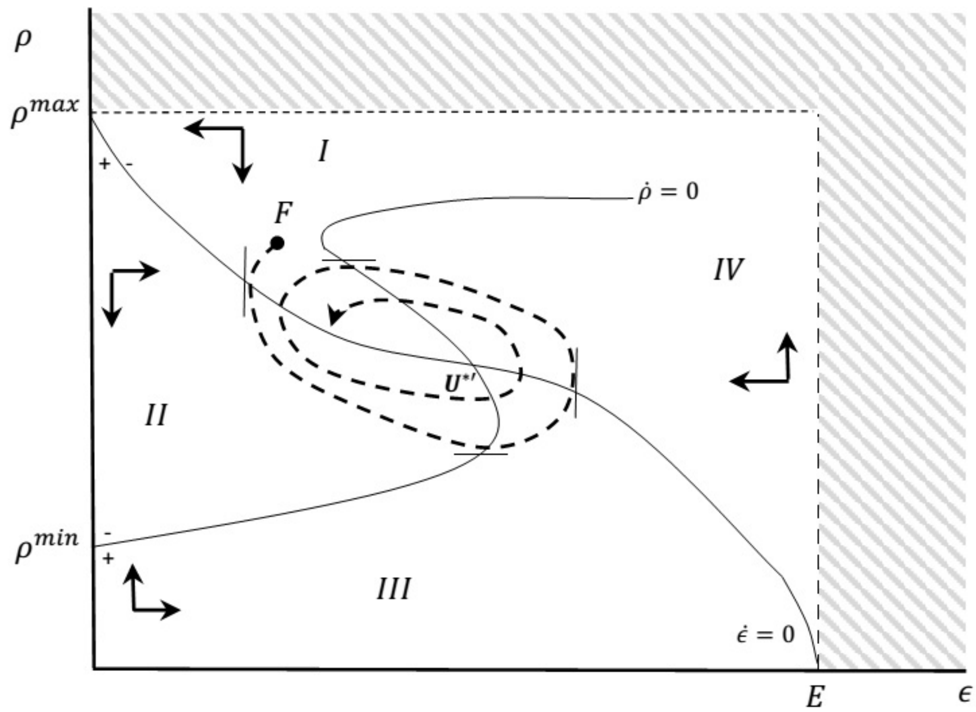


Figure 3.3: A locally asymptotically stable equilibrium point in the surplus labor economy.

is plausible to think, for instance, that the natural rate of environmental regeneration is relatively low in response to externalities related to land degradation, poisoned water, and atmospheric pollution concentration than for indoor pollution (burning of biomass); thus, stability might be a regular feature of the latter. However, in the most common environmental problems, a lower β should be expected.

The sensitivity of the level of environmental quality to output expansion is also important. It can be argued, however, that in the absence of discrete effects, ω, is relatively small. It is only under anthropogenic environmental disasters that a relatively high ω should be expected.[13]

At the same time, it is difficult to assume that the environmental adjustment costs related to different externalities are relatively homogenous. Intuitively, what matters the most for the argument is how rapid the output expansion responds to a change in the level of environmental quality and thus in the environmental adjustment costs, h_ϵ. To treat the possibility of stability as a special case in the interaction between economic growth

[13] As an example of the destructive potential of capitalist activities, it is worth noting the recent collapse of a mining dam that occurred in the Brazilian state of Minas Gerais in 2015. It was one of the biggest environmental disasters in Brazilian, and maybe in Latin American, history. See Massarani (2016).

and environmental quality, I suppose that this sensitivity is relatively low compared to the adjustment process in the capital–output ratio over the cycle.

3.3.1 An economic interpretation of the cycles

This section provides an economic interpretation of the vicious circle. A limit cycle need not to be unique, as it is sensitive to the initial conditions of the economy. Figure 3.2 presents one of the possible branches covered in the system. Note that the set of trajectories must exhibit the same oscillatory behavior; thus, the economy is represented without the loss of generality.[14]

Consider that the economy is at point A in a situation with a relatively high level of output–capital ratio and share of profits in income but a relatively low level of environmental quality. The adjustment costs corresponding to environmental quality signals are relatively high, given the negative pressure that economic activity exerts on the environment. This negative effect helps to compress the rate of output expansion below the rate of capital accumulation. The output–capital ratio is therefore falling at A. As ρ is falling, the level of investment and effective demand is also falling; thus equilibrium in the goods market is maintained by a reduction in the profit share. In contrast, the environmental quality is increasing, given the diminishing negative scale effects on the environment, and the economy is moving toward region II.

At B, the output-capital ratio and profit share are relatively low, but with relatively average levels of ϵ. The smaller ρ compresses capital accumulation, which then drops below the rate of output expansion, thus increasing ρ. Investment is increasing, and the effective demand changes raises π, which restores the equilibrium in the goods market. As the profit share is increasing, and adjustment costs that come from the level of environmental quality are decreasing (for this level of ϵ), the output is growing at a rate that does not compromise the expansion in the level of environmental quality, with the economy moving toward region III. However, when the system enters region IV, output expansion starts to compromise environmental quality since the negative effects of the scale of the economy

[14] For illustrative purposes, the reader may think of the negative environmental externality as the local emission of a toxic industrial pollutant, which in such a case is clearly pro-cyclical. As the health effects are sensitive to the atmospheric flow of this pollutant, the growth rate of environmental quality is also compatible with the business cycle.

are greater than the natural growth rate (the environmental capacity of regeneration, thus decreasing labor productivity). Such an effect is represented by point C.

After a while, the corresponding decrease in the level of environmental quality, given the environmental deterioration, begins to exert a stronger pressure on the adjustment costs, which in turn, starts to compress the output expansion, with the economy moving toward region I. Furthermore, at point D, the output–capital ratio and profit share are relatively high, and the capital accumulation rate is above the growth rate of output. The corresponding negative changes in effective demand are accommodated by reductions in the profit share, thus exerting further downward pressure on $\hat{X}$. Even with such a decrease, the level of environmental quality is relatively low in such a way that ϵ and ρ are both declining.

Therefore, without exogenous intervention, such a cyclical counter-clockwise behavior will go on perceptually in this dual economy. Note that this oscillatory behavior is possible under the assumption of free utilization of environmental quality in the sense that there is no vector of prices clearing the "environmental market." What prevents the economy from achieving complete environmental decline is the rise in adjustment costs when the level of environmental quality is relatively low. Regarding the possibility of stability presented in Figure 3.3, the properties of the oscillatory behavior are similar, but the economy converges to the stable focus, U^*. In such a case, if the sensitivity of the environmental quality to output expansion is relatively high and the natural rate of regeneration of the environment is relatively low, the economy may eventually experience a decline.

The present model is also related to (and somehow inspired by) an interesting environmental macromodel of economic growth: the Brander and Taylor (1998) Ricardo-Malthus general equilibrium model of renewable resource use. They model population dynamics related to the Lotka–Volterra predator–prey model, with the humans as the predator and the resources base as the prey, offering a possible explanation for the rise and fall of past civilizations such as Easter Island. In the model, it is the population growth that degrades the resource base. In turn, the reduction of the resource stocks exerts a downward effect on the fertility rate of population. Such dynamics also result in an oscillatory behavior of the system. Locally stable cycles arise because the resource base has a slow rate of regeneration, but it focus is on the long run.

The present results have some similarities with the work of Brander and Taylor (1998) in the sense that a low natural growth rate (a low rate of regeneration of the environmental quality) may eventually compromise economic activity. This can happen only in the setting illustrated in Figure 3.3, in which a strong negative labor productivity effect generates stability. However, I extended the results in several directions. I combine environmental and effective demand issues via the relationship between capital–output ratio and environmental quality in a medium run vicious circle. More importantly, capital accumulation is included in the model, in with which the role of the capitalist sector is explicitly analyzed. It is this conflictive relation that creates the conditions for perpetual oscillation in the medium run, instead of asymptotically stable behavior in the long run.

In concluding, a brief political economy discussion is in order. One may wonder whether the behavior of the system described in this paper underestimates the power of institutional change since we should expect the possible creation of efficiency resource arrangements through market solutions or institutional evolution, even in low-income developing economies. Note that a market solution (a price vector for the negative externalities) only magnifies the sensitivity of the output expansion to changes in the level of environmental quality through the occurrence of more direct environmental adjustment costs. It is only if these costs create incentives for the adoption of clean technologies, for instance, that an eventual market solution helps the economy to solve or at least reduce the operation of the vicious circle. However, it seems unlikely that a low-income developing economy, if left to the free play of its structural forces, and facing poverty, education, and health development problems, is capable of generating, or even adopting, clean technologies to reduce its negative externalities on the environment.

Meanwhile, even without market or governmental (taxation) solutions, in some way, it is also possible that the population of agents endogenously learns to solve its common pool problem through institutional co-evolution (Bowles, 2004). This argument brings me to the seminal work of Elinor Ostrom (see Ostrom (1990) and Ostrom et al. (1994)), which shows that primitive and advanced societies can eventually resolve the common pool problem through cooperative arrangements; however, this does not mean that all of them will do so. As described in Ostrom (1990), in the end, this is an empirical question, and she collected evidence to determine which factors favor the survival of efficient institutions.

Brander and Taylor (1998) point out that the most important favorable factor is an agreed-upon and correct understanding of the problem. They use a modern example, explaining that it was not possible to settle upon an effective response to ozone deterioration until there was substantial agreement that the problem existed and that the mechanism causing the problem was anthropogenic. Ostrom (1990) also points out other several important factors: the size of the resource stock, such as the size and homogeneity of the group, the existence of a leadership, and the likelihood of punishment in case of deviation from the cooperative equilibrium.

Therefore, it is not clear that all low-income developing countries are capable of promoting this cooperative outcome, thus reducing the negative externalities on the environment and decreasing the sensitivity of the output expansion to the corresponding environmental adjustment costs. From an empirical perspective, however, certain development agencies are carrying out initiatives in an attempt to promote these changes in developing countries such as Rwanda. As mentioned in the introduction, Rwanda has serious problems with land degradation that compromises GDP. The Poverty-Environment Initiative of the United Nations Development Programme (UNDP) and the United Nations Environment Programme (UNEP) in this country, for instance, focuses on enhancing the contribution of sound environmental management to poverty reduction, sustainable economic growth, and the achievement of the Millennium Development Goals. In parallel to the present results, it is an important political attempt to reduce the occurrence of vicious circles in low-income developing economies.

3.4 Conclusions

This paper argues that when environmental adjustment costs are binding already in the medium run in low-income developing economies with relatively low levels of environmental quality, we should consider turning the focus from a long run well-behaved trajectory of economic growth to a possible new channel of endogenous cyclical fluctuations. One of the contributions of this paper is to model such a possibility through a simple *Harrodian* macrodynamic model of economic growth that explores, in one of its relevant aspects, this conflictive interaction between environmental quality and economic growth.

From a methodological perspective, the current results extend the theoretical explanatory power of the *Harrodian* models, showing that the environmental dynamics may operate as another taming mechanism for instability raised by effective demand issues.

Essentially, this occurs through the interaction between environmental adjustment costs in the production process and its negative scale effects that endogenously change the level of environmental quality in the whole economy, thus affecting the health of the labor force and the productivity of factory workers.

The same mechanism that "stabilizes" the Harrodian instability may create a region of perpetual vicious cycles, from which this dual economy may never leave without firstly resolving its exploitative relationship with the environment. A dirty growth strategy is environmentally unsustainable in the medium run because the effective demand that expands investment also exerts a downward pressure on the environmental quality. In turn, a fall in the level of environmental quality raises the environmental adjustment costs of production. In this sense, the conflictive relation between effective demand (economic growth) and the environment (environmental quality) illustrates a Keynesian perspective for the environmental problem of some low-income developing economies.

Possible theoretical extensions of the present model could incorporate the role of abatement efforts from a Keynesian perspective, which should include an explicit abatement function affecting investment decisions. In addition, the adoption of clean technology could exert a powerful role in avoiding the emergence of such endogenous cyclical fluctuations.

Chapter 4

Growth, Distribution, and a Transitional Dynamics to Clean Technology

4.1 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

[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

(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 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

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.

[5] See Bowles (2004).

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 4.2 presents the structure of the model, followed by the description of its behavioral foundation in Section 4.3. In Section 4.4, the macrodynamics effects are analyzed in detail. The paper closes with some final remarks.

4.2 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 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 *wageâprofit* for the c-firm and d-firm, respectively, as follows:

[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.

$$w_c = x_c[1 - \frac{(r_c + \tau_c)}{\rho_c}], \tag{4.1}$$

$$w_d = x_d[1 - \frac{(r_d + \tau_d)}{\rho_d}]. \tag{4.2}$$

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 4.2.1).

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

$$\omega_c = x_c(1 - \frac{g_{k_c}}{\rho_c}), \tag{4.3}$$

$$\omega_d = x_d(1 - \frac{g_{k_d}}{\rho_d}). \tag{4.4}$$

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 (4.1) and (4.2) as (4.3) and (4.4) to express this aggregate behavior as follows:

$$\bar{w} = px_c[1 - \frac{(r_c + \tau_c)}{\rho_c}] + (1 - p)x_d[1 - \frac{(r_d + \tau_d)}{\rho_c}], \tag{4.5}$$

$$\bar{\omega} = px_c(1 - \frac{g_{k_c}}{\rho_c}) + (1 - p)x_d(1 - \frac{g_{k_d}}{\rho_d}), \tag{4.6}$$

which represents the *average growth and distribution schedule* in Figure 4.1.

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

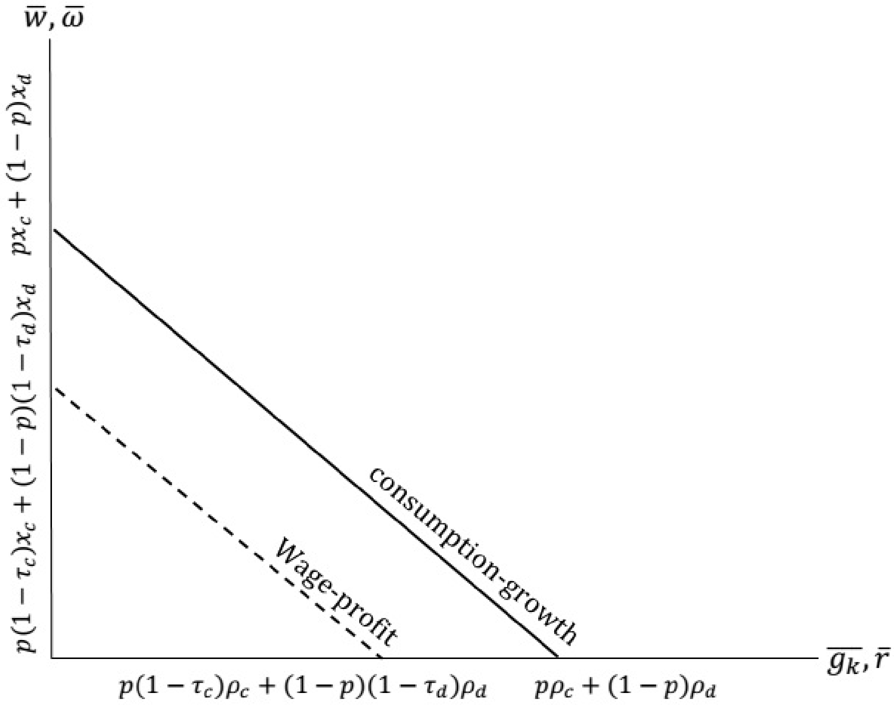


Figure 4.1: The average growth and distribution schedule.

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, $\partial\bar{w}/\partial p < 0$.

4.2.1 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 (4.1) and (4.2) as follows:

$$r_c = \frac{x_c - w_c}{k} - \tau_c, \tag{4.7}$$

$$r_d = \frac{x_d - w_d}{k} - \tau_d. \tag{4.8}$$

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:

$$p_{t+1} = p - \alpha p(1-p)\lambda_c \beta(r_d - r_c) + \alpha p(1-p)(1-\lambda_d)\beta(r_c - r_d), \tag{4.9}$$

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:

$$\frac{dp}{dt} = \alpha p(1-p)\beta(r_c - r_d), \tag{4.10}$$

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 (4.7) and (4.8), it is readily seen that the two unique values of p that stabilize (4.9) 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 number of researchers, and the body of literature on the topic is growing.

[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.

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]

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

$$\tau_c = \gamma_o - \gamma_1 p, \tag{4.11}$$

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 to changes in the stock reserves, for instance. I will call this setting of the *non-regulated regime*. In this game, we can use (4.11) in (4.7), and treat τ_d as parametric in (4.8).

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:

$$G = (1 - p)X, \tag{4.12}$$

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:

$$\hat{\epsilon} = \chi(E - \epsilon) - (1 - \phi\mu)(1 - p)X, \tag{4.13}$$

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

In the regulated regime, we can use (4.11) in (4.7), but now, (4.8) is replaced by the following equation:

$$r_d = \frac{x_d - w_d - \tau_d}{k}. \tag{4.14}$$

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, (4.7), (4.8), and (4.14), 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

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

great deal of inspiration from these previous theoretical initiatives.

4.3 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, (4.10), 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:

$$g = s\bar{r} = s[pr_c + (1-p)r_d], \tag{4.15}$$

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 (4.12), 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 the model as evolutionary.[11]

4.3.1 The non-regulated regime

In the non-regulated regime, we use (4.11) and (4.7) into (4.10) to determine the new replicator dynamic equation:

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

$$\frac{dp}{dt} = \alpha p(1-p)\beta[r_c(p) - r_d], \tag{4.16}$$

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:

$$\left.\frac{\partial \dot{p}}{\partial p}\right|_{(p^*=0)} = \alpha\beta(\rho_c - \rho_d + \tau_d - \gamma_0), \tag{4.17}$$

$$\left.\frac{\partial \dot{p}}{\partial p}\right|_{(p^*=1)} = (\alpha\beta - 2\alpha\beta)[\gamma_1 + (\rho_c - \rho_d + \tau_d - \gamma_0)]. \tag{4.18}$$

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 (4.18). 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:

$$p^* = \frac{\rho_d - \rho_c + \gamma_0 - \tau_D}{\gamma_1}, \tag{4.19}$$

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 4.2 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 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 (4.19), 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.

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:

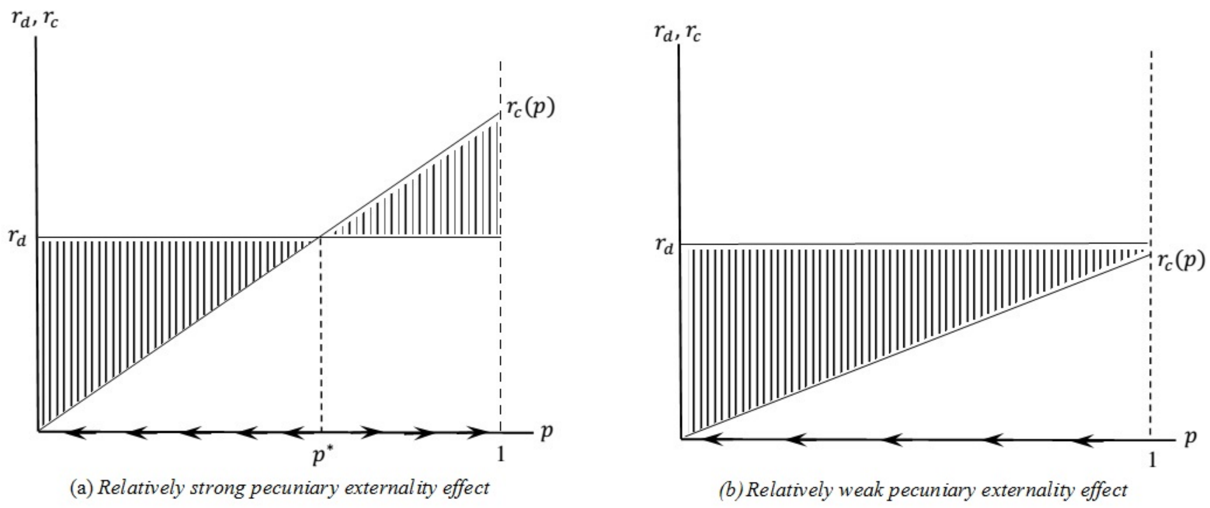


Figure 4.2: Transitional dynamics in the non-regulated regime.

$$r(p^*) \equiv r(0) = \left(\frac{x_d - w_d}{k} - \tau_d \right), \tag{4.20}$$

$$r(p^*) \equiv r(1) = \left(\frac{x_c - w_c}{k} - \gamma_0 + \gamma_1 \right). \tag{4.21}$$

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 (4.20) and (4.21). Figure 4.3 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 4.3 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.

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.

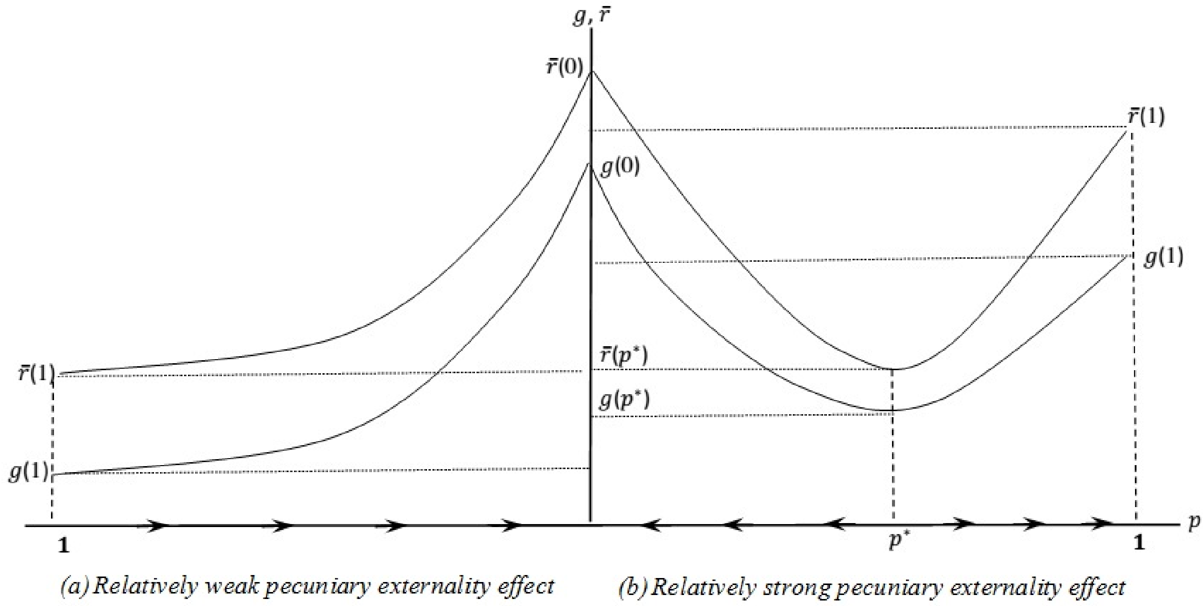


Figure 4.3: Growth and distributional effects in the non-regulated regime.

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 4.3; thus, this is more likely the achievement, or overcoming, of the previous pattern of income distribution and economic growth, even if possibly slowly.

4.3.2 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 (4.11), (4.7), and (4.14) into (4.10), the new replicator dynamic equation becomes the following:

$$\frac{dp}{dt} = \alpha p(1-p)\beta[r_c(p) - r_d(p)], \tag{4.22}$$

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:

$$\left.\frac{\partial \dot{p}}{\partial p}\right|_{(p^*=0)} = \alpha\beta[\rho_c - \rho_d - \gamma_0 + \mu\rho_d^g], \tag{4.23}$$

$$\left.\frac{\partial \dot{p}}{\partial p}\right|_{(p^*=1)} = (\alpha\beta - 2\alpha\beta)[\gamma_1 + (\rho_c - \rho_d - \gamma_0)], \tag{4.24}$$

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 (4.13). 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 4.4 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:

$$p^* = \frac{\rho_c - \rho_d - \gamma_0 + \mu\rho_d^g}{\mu\rho_d^g - \gamma_1}, \tag{4.25}$$

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

Panel (a) in Figure 4.4 presents a result similar to the one depicted in Figure 4.2, panel (a): the stability case. Note, however, that for similar reasonable parameters, the illustration in Figure 4.4 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 (4.25). The growth and distributional effects will present a similar pattern, illustrated in Figure 4.3, 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.

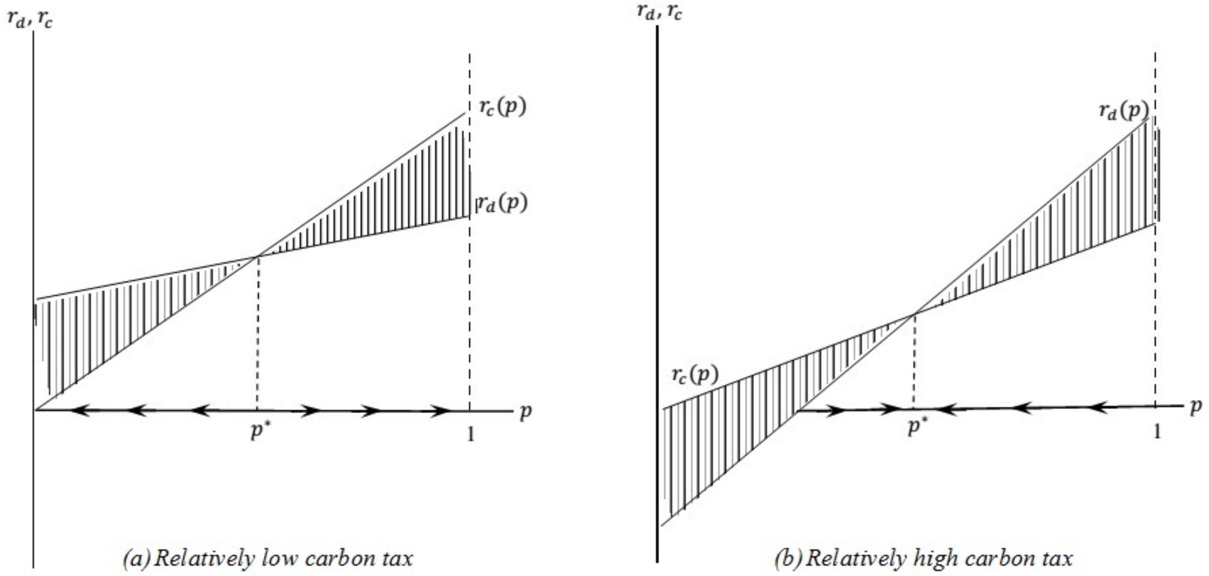


Figure 4.4: Transitional dynamics in the regulated regime.

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 4.5, 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.

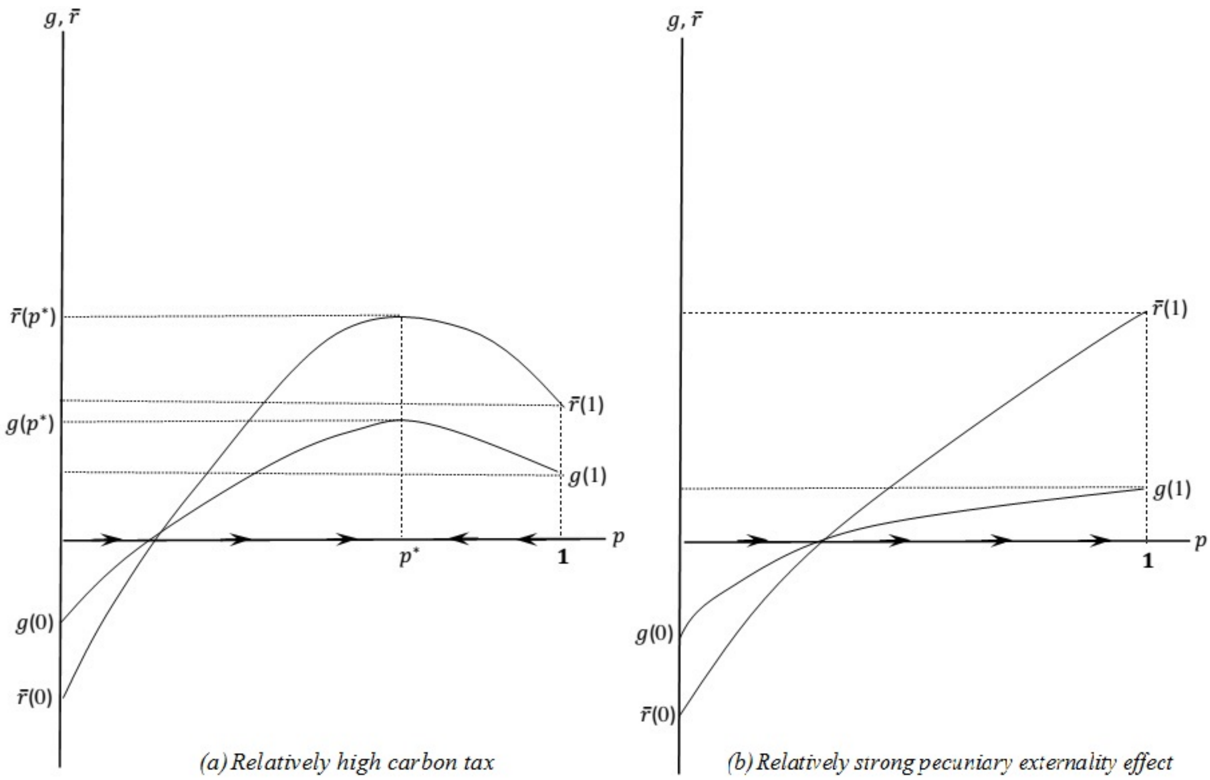


Figure 4.5: Growth and distributional effects in the regulated regime.

From the environmental and ecological perspective, the ideal solution is only achieved if the 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 4.5, 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 (4.8). 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.

4.4 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.

Chapter 5

Final Remarks

All capitalist economies have a predatory relation with the environment, even if these may be at different levels. There is significant, if not conclusive, evidence relating such a predatory relation to environmental degradation and anthropogenic climate change, more broadly, so that they are now issues of public concern and central importance. This begs the following question: What do macroeconomists know about it?

Unfortunately, the relationship between macroeconomics and the environment is not well understood. On the one hand, our knowledge about the science involved in such issues and its relation with economics is limited. On the other hand, the quality of environmental data is relatively poor, and we cannot estimate robust empirical evidence relating the negative environmental externalities to economic aggregates. So, what can we do? There is a relative consensus between environmental macroeconomists that we should focus on formulating simple theoretical models that can clarify our understanding about the relation between macroeconomics and the environment either in its medium- or long-run dimension.

In this context, is there any particular reason to focus on a single approach such as the orthodox or post-Keynesian answer to the problem? The answer, in my view, is no. The reason is that answers to environmental challenges such as degradation and climate change are sensitive to the internal consistency of macroeconomic models and their implicit or explicit assumption concerning sustainable development. I would argue, therefore, that pluralism is beneficial for these questions at hand; hand; thus, focusing on a particular framework is not desirable by its one sake.

The present Dissertation incorporates much of this spirit of pluralism. I have developed three theoretical models that incorporate different environmental problems and implicit or explicit weak and strong sustainability assumptions. I have focused on alternative macromodels because the heterodox tradition has largely ignored sustainable development issues. It is ironic that a set of theories and models concerned with what neoclassical economists call market failures are, in fact, structural deficiencies, have ignored the perhaps most important of them: the negative externalities on the environment.

Therefore, the first contribution of the present Dissertation is to model environmental sustainability issues in alternative macroeconomic models. Here I have explored environmental issues involving the medium (fluctuations) and long run (economic growth and economic development) perspective of the macroeconomy. The medium-run dimension, despite being surrounded by a great deal of controversy, is modeled in a particularly novel way. The other two essays address a long run perspective.

In the first essay (Chapter 2), I present "a green Lewis development model". The first contribution of this essay is to extend a Lewis development model to an environmental dimension. To the best of my knowledge, this is the first attempt to do so. I justify this extension using recent and robust econometric evidence on the relation between pollution and labor productivity. Motivated by the recent contribution of the so-called "green Solow model" (Brock and Taylor, 2010), I was interested in investigating whether developing countries are not structurally any different in the sense that a simple environmental policy can prevent them from achieving economic maturity (in a *Kaldorian* sense). The reader should recall that "the green Solow model" has an optimist view about sustainable development in developing countries: there is no endogenous force that is capable of preventing them achieving economic maturity, even in the face of abatement policies that compromise a fraction of their gross savings. In fact, this result is in contrast with many of the claims that developing countries make during international environmental negotiations.

Interestingly, the essay finds that a developing dual economy that has to comply with a pollution abatement requirement may fall in what I dub an ecological development trap and therefore may fail to reach mature development. Moreover, once in such trap, a developing dual economy is either already experiencing or will eventually come to experience a *Kaldor–Myrdal* circular and cumulative causation process of decline in capital intensity and environmental quality. Fortunately, however, a developing dual economy that happens to fall in such trap can be released from it not only through a standard Big Push, in the spirit of Rosenstein–Rodan, but also by means of what I dub an Environmental Big Push. The latter could be based, for instance, on the adoption of international redress and compensation mechanisms in favor of developing economies. While the case for a standard Big Push is quite well established in the economic development literature, this essay contributes to the environmental macroeconomics literature by providing a sound theoretical rationale for an Environmental Big Push.

The essay, thus, can be read as being more closely related to the weak sustainability assumption. The reason for this is that I have assumed that all environmental impact is potentially reversible in the long run, and that there is some degree of substitution among physical capital stock and the level of environmental quality. To what extent does my main result, the ecological development trap, depend on this sustainability assumption? Certainly, it depends a great deal on it; however, the weak sustainability assumption makes the result stronger. If, on the other hand, I had supposed the strong sustainability assumption, the ecological development trap would become more pervasive since there would be no reversibility in the environmental impact in the long run.

In the second essay (Chapter 3), I explore the issue of reverse causality in the environmental Kuznets curve. International development agencies have discussed and addressed the situation of some developing countries that have relatively low levels of environmental quality, such as Rwanda, for example. In such countries, much of the macroeconomic instability involving economic growth is caused by their environment fragility in response to soil erosion, poisoned water resources, or toxic pollution in the local atmosphere. An economic development strategy based on the environment Kuznets curve may eventually result in an unsustainable vicious circle in these regions, possibly even in the medium run.

What is important to the argument and hence the contribution of this second essay is that it is necessary to understand that in such dual low-income developing economies, the relatively low levels of environmental quality result in a cost that is binding in the short run, and not only in the long run, as we are accustomed to thinking. This cost arises from the negative effects of pollution (not all sources of pollution, of course) on the labor force. Based on robust and recent empirical evidence, I refer to those these costs as environmental adjustment costs. The model incorporates such environmental adjustment costs in a a post-Keynesian framework: the *Harrodian* benchmark. The reason for this is that the *Harrodian* model supposes that the output is not fully flexible in the short run; instead, it only slowly responds to unexpected shocks in aggregate demand. This slow adjustment is justified by the existence of adjustment costs. In this second essay, I examined how a developing economy is likely to behave in a context like that.

The well trained long run mind would choose to relate variations in the level of environmental quality to capital accumulation, thus exploring an eventual occurrence of long term vicious circles (which is natural and easy in a *Harrodian* model). However, I have deliberately choosen to use the capacity utilization as an accommodating variable. The reason for this is that I believe that much of the macroeconomic medium run instability in these countries is due to the relatively low level of environmental quality. My main contribution is to show that the environmental adjustment costs may also contribute to the emergence of perpetual vicious circles in dual low-income economies with relatively low levels of environmental quality.

Interestingly, the model thus creates an innovative link between effective demand and environmental quality. A rise in effective demand is associated with a fall in the level of environmental quality. In addition, to explicitly mention the *Harrodian* instability "problem", effective demand is endogenously linked to the natural growth rate of the environment. Such an apparently naive result has an important implication for ecological and environmental macroeconomics: if the environmental adjustment costs are taken into account, the model shows that there is a long run trajectory linking economic growth (the warranted growth rate) to the behavior of the environment (the natural growth rate). What the model emphasizes, in line with its *Harrodian* specification, is that this trajectory is cyclically unstable and not well behaved, as is argued by most neoclassical models based on the unidirectional (and endogenous) prediction of the environmental Kuznets curve.

The model can be read as implicitly in line with the strong sustainability assumption. This is because the environment does not play a passive role in the model. The non-substitutability assumption, by means of a fixed–proportions production function, is also important. The main contribution, thus, relates to the recent movement to model sustainable development issues in the post-Keynesian tradition, as suggested by Taylor et al. (2015).

The first two essays have a characteristic in common: there is no room for the adoption of clean technology. This should not be understood as a limitation. On the contrary, the previous contributions show that in the absence of clean technical change, the relation between the macroeconomy and the environment is subjected to multiple equilibria and cyclical instability. However, at some moment, the possibility of adopting clean technology has to be faced; this is so precisely the main objective of the third (and last) essay (Chapter 4).

In the third essay, I explored what accounts for the diffusion and maybe the non-use of clean technology in a competitive environment. This is a very timely issue. The old growth models and most of the recent economic models of climate change assume exogenous technical change. Recently, however, Acemoglu et al. (2016) have questioned this view. They formulated an endogenous growth model with direct technical change that accounts for most of the dynamics involved in the invention and the adoption of new clean techniques. However, several questions regarding the empirical evidence remain open.

Thus, the third essay addresses two of several important issues: the existence of strategic complementarity behavior among firms and the role of carbon taxes in the process of technical choice. I have modeled these issues an using an evolutionary game-theoretic approach. Evolutionary game theory offers a novel behavioral foundation for the microeconomics of clean technical change. The focus on microeconomics was primarily to understand macrodynamics so that I have incorporated this foundation in a classical-Marxian description of the macroeconomy. The classical–Marxian model is helpful in exploring the problem of technical choice, especially because the classical economists and Marx were quite concerned with the role of technology in the capitalist society.

The main preliminary contributions of the essay are the following. First, it shows that a mixed-strategy equilibrium in which firms produce using clean and dirty technology is a possible evolutionary outcome. The result illustrates an empirical evidence that different techniques of production may survive in a competitive environment. Furthermore, in some cases, the carbon taxes set by the government can create a dirty technological trap. The political question then becomes if such a trap (the mixed-strategy equilibrium) will be closer to the full specialization in dirty or clean technology. In the model, the main economic mechanism that can prevent firms from being trapped close to the pure specialization in dirty technology is the pecuniary externality effect on the adoption of clean technology.

The second contribution is to show that potentially beneficial environmental outcomes require exogenous interventions, which in the paper assumes the format of government policies. These policies may promote discontinuous shocks (investments) in the adoption of clean technology as well the "correct" calibration of carbon taxes. Inevitably, however, the ideal environmental scenario in which all firms use clean technology and the environmental quality converges to it maximum carrying capacity point, is only achieved through an initial adverse macroeconomic impact. Such an impact is a profit-reducing shock on functional income distribution, and thus, a fall in economic growth. Meanwhile, such a result is not similar to a degrowth strategy, which requires some level of social transformation. The present result implies that the degrowth is temporary, so that that at some time, profits will increase based on clean technology.

The third essay is suitable to both sustainability assumptions because both ecological and environmental economics assume that clean technological change is important in order to achieve sustainable development. My contribution, however, reveals that the transitional dynamics to clean technology are not easy and calm; instead, they are a conflictual process that may eventually reduce capital accumulation for a considerable amount of time. The result thus adds to the claim against the so-called climate policy ramp.

Motivated by all these specific contributions to economics, I conclude that the present Dissertation has achieved its main objective of developing alternative macromodels that explore, in some of their many relevant aspects, the macroeconomic implications of some environmental and ecological economics concerns. The central message is that our intuition and understanding about the relationship between the macroeconomy and the environment can be broadened rather than shaped by a particular macroeconomic framework or assumption concerning sustainable development. The progress of the field requires that we are able to develop and study all approaches, so that economists should have the opportunity to have their intuition about the economics of the environment shaped by all of them.

One of the main limitations of the present Dissertation is that I treat the negative environmental externalities as a local effect. Most externalities are, in fact local; however, greenhouse gas emissions, one of the most important externalities, and one that has attracted a great deal of attention, is global. There is no logical shortcoming in approaching only the local aspect of the negative externalities. As a matter of logic, I tend to believe that an open setting would make the ecological development trap and the vicious circles, for instance, even more pervasive. Meanwhile, the global treatment of the negative environmental externalities should be pursued as future research. It would be particularly interesting to examine environmental issues in open macroeconomic models.

In the first essay, for instance, the main result indicates that if left to free play of its structural forces, developing countries cannot converge to the mature phase. Thus, a natural step is to stress the role of developed countries in this international political scenario. Can developed countries help developing countries to converge without destroying the planet? In addition, as much of the technological knowledge is developed in the rich countries, developed countries may exert an important influence on the adoption of clean technology in developing countries. Thus, an extension of the the third essay is in order. However, will this process generate divergence or convergence in terms of *per capita* income? North–South models can illuminate this relevant question.

These are very timely issues since the relationship between the environment, open macroeconomics, and income distribution has not received sufficient attention. The analysis of the relation between global warming and structural change and its consequences for developing countries may finally be a necessary step before addressing the effectiveness of sustainable development policies. These latter questions arguably present the greatest challenge to environmental and ecological macroeconomics.

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