Choosing the Direction:

Investment, the Environment, and Economic Development

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PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Universiteit van Tilburg, op gezag van de rector magnificus, prof. dr. F.A. van der Duyn Schouten, in het openbaar te verdedigen ten overstaan van een door het college voor promoties aangewezen commissie in de aula van de Universiteit op vrijdag 27 october 2006 om 10.15 uur door

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prof.dr. A. J. de Zeeuw

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"It was the best of times, it was the worst of times,
it was the age of wisdom, it was the age of foolishness..."

Charles Dickens, *A Tale of Two Cities*.

The title of this thesis is about choices of direction; looking back at the three years I have spent in Tilburg, I realize that this is far from accidental. Coming to the Netherlands to undertake my PhD studies represented a clear change of direction, away from my previous life (not only professionally) and towards a different future. It wasn't an easy choice to make then, but I now know that it was the best choice I could make.

Writing a dissertation is a challenging process. There are times (the best ones) when the enthusiasm about a topic, a new idea or simply talking to people who share the same interests and the same passion makes it seem an easy task. But of course it is not. Research can be frustrating business, trying to prove the same result for the n-th time ($n \to \infty$ sometimes, eh Piotr?!) when nothing seems to work, naturally spawns a very strong desire to quit it all - these are the worst of times... I am writing these lines because I know that it is only thanks to the people I am about to mention that the good times outweighted the bad ones.

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Dublin, August 2006

CONTENTS

INTRODUCTION

Is technological change good for the environment in a globalized world, or does it rather lead to more pollution? Are climate policies enlightened attempts to preserve the environment for future generations, or are they just futile burdens on economic systems? Do efforts to increase the level of education in developing countries lead to faster economic growth, or do they represent a waste of already scarce resources? These are some of the themes we investigate in this dissertation: the aim of this work is to contribute some answers to questions that touch our life, every day.

The focus of this thesis is on the interrelations between technological change, environmental policy and environmental quality, on the one hand; and between technological change, human capital accumulation and economic development, on the other. Throughout this work we claim that, to understand these complex phenomena, we need to take into account both the general equilibrium features of the problems, i.e. the feed-backs between technological change and inputs (such as resources and skills) supply; and the dynamic issues involved, i.e. the evolution over time of the level, and of the composition of technology and inputs.

Consider, for example, the interaction between environmental policy, technological change, and pollution in a globalized world. Many argue that globalization is just another way for first world countries to exploit the third world. In their view, stringent environmental standards set by developed countries expel polluting industries, forced to relocate in countries with laxer environmental regulation. Opponents of this view, on the other hand, see environmental regulation as the necessary instrument to channel technical progress in a more energy- and pollution-saving direction. They emphasize the role of technology transfer from the developed to the developing world as the key to achieve sustainability. We argue that the *feed-backs* between international trade and technological change are richer than either of these views suggest. Indeed, the development of technologies reacts to economic incentives. At the same time, however, the availability of cleaner and more efficient technologies leads to an increase in pollution, if the demand for polluting goods does not decrease. Hence, both views hold part of the truth, and different outcomes may obtain in different situations. By emphasizing the key determinants of these outcomes, we point at the elements that need to be taken into account when assessing specific cases.

The fact that innovators actually *choose* what kind of technology to *invest* in is crucial in this respect. One of the recurrent ideas of this thesis is that technological change is the result of purposive activities of research and development (R&D), and that the choice of the *kind of technology* which is developed depends on the expected profits to be made by exploiting it. Investments in R&D are incurred only as long as there are returns to be reaped; and the type of innovation that actually occurs – whether, for example, it pays more to devote resources to the improvement of the performance of a computer like the one I am typing this introduction on, or to work to make it more energy efficient – is, in the end, just a matter of economic incentives.

Equally important, however, is the understanding that the demand for resources to be used in production – e.g. energy, or the environment's capacity to absorb pollution – depends critically on the available technology: firms trying to maximize profits will naturally tend to demand more of the resource, if they become more productive *cœteris paribus*. Thus, *environmental* outcomes are determined by the contemporaneous working of demand (preference) and supply (technology) factors: the endogeneity of the links between technology and resource use is another of the core themes of the work at hand.

As another example, think of the impacts of the emigration of skilled workers on a developing country's development performance. The fact that emigration is possible leads workers to pursue higher levels of education than they would otherwise. This might have ultimately a positive effect, provided that not all the skilled workers eventually leave. However, workers might want to specialize in fields that are in high demand abroad, but not very productive domestically. Hence, the *composition of skills* that are accumulated is sub-optimal and resources are not used in the most productive way, so that the growth performance of the country is lower than it could be. The fact that agents can *choose the direction* of their investment, thus leads to a slower pace of *economic development*.

The examples sketched above show that a thorough understanding of these complex and interrelated processes is fundamental when looking for meaningful economic answers to the questions asked at the beginning. In this thesis we start from this realization and investigate such diverse topics as North-South trade pollution havens, international differences in climate policy and innovation, resource-augmenting technical change in capital-resource economies, and the links between migration, technological development and growth in developing countries.

Our analysis is consistently carried out by means of dynamic general equilibrium models, featuring incentive-driven accumulation of knowledge, and is thus firmly rooted in the tradition of growth theory. However, as mentioned above, the four chapters that compose this dissertation all have a special focus on the role of factors' *composition*, rather than on their *level*, in determining the relevant outcomes. Behind this modelling choice is the belief that a more detailed level of analysis than usually employed in economic models is necessary to (try to) understand the complex interplay between economic incentives, factors' accumulation, and policy measures in many fields. The brief *excursus* in the literature that follows will help clarify this point.

A BRIEF OVERVIEW OF THE LITERATURE

The long-standing focus of growth theory on the accumulation (and hence the level) of productive inputs, markedly of physical capital, has deep roots dating back to the early days of economics as a science. Adam Smith (1776) was the first to point out that the wealth of a nation depends upon the size of the market (and hence on capital and labour availability), because this is what determines the division of labour and the proportion of the population engaged in productive activities. He also remarked that it is the accumulation of wealth (capital) to cause economic development. Other classical economists such as Thomas Malthus (1798) and David Ricardo (1817) also focused on the determinants of growth, and underlined the role of capital (and technology) accumulation as means to obtain economic growth. They emphasized, however, the impossibility of sustained growth in the long-run, due to the pervasiveness of decreasing returns to productive factors.

Over a century later, with an eye at the broader substitution possibilities between factors implied by the neoclassical aggregate production function, Solow (1956) and Swan (1956) firmly established capital accumulation as the key to understanding economic growth. In line with the classics, the central prediction of neoclassical growth models is that, due to diminishing returns to each input, in the absence of continuing improvements in technology, percapita growth must eventually cease. To overcome this deficiency, neoclassical growth theorists in the 1950's and 1960's generally assumed an exogenous process of technological progress. In this way they could reconcile their framework with the possibility of long-run growth. Building on the pioneering work of Ramsey (1928), Cass (1965) and Koopmans (1965) introduced optimal saving decisions in the Solow-Swan framework and *de facto* completed the neoclassical growth framework. By focusing on the role of capital accumulation and not addressing the issue of the determinants of technological change, however, neoclassical growth theory in fact left the fundamental question, what causes growth, unanswered.

Serious attempts to incorporate a theory of technological change in the neoclassical growth model had to wait for the diffusion of tractable models of imperfect competition (e.g. Dixit and Stiglitz 1977). The so-called *new growth theory*, started by such contributions as Romer (1986) and (1990), Aghion and Howitt (1992), and Grossman and Helpman (1991), presents models featuring purposive R&D activities, rewarded by the monopoly power enjoyed by inventors.

This new literature added an important dimension to the debate on economic growth, underlying the role of knowledge accumulation, rather than capital accumulation, in the process of growth.

This was a welcome and long-awaited development in the growth literature. Indeed, for many decades an influential literature had been developing, which stated quite clearly that the growth rate of output seemed to be explained to a great extent by what came to be known as the *Solow residual* rather than by factors' accumulation. Easterly and Levine, in a paper aptly entitled "*It's not factor accumulation*" (2001), for example, present a critical discussion of this literature and conclude that "*when comparing growth experiences across many countries, 'something else' – besides factor accumulation – plays a prominent role in explaining differences in economic performances*"[1]. The vast literature on *Growth Accounting* developed with the aim of evaluating the 'proximate causes' of growth, i.e. understanding the sources of economic growth, by estimating the contributions of each productive inputs to output growth.

A common feature of growth accounting exercises is that conventional inputs (mainly capital and labour) seem to explain only a small fraction of total output growth, leading to the puzzling conclusion that the residual, this "measure of our ignorance" in the words of Moses Abramovitz, accounts for

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[1] Ibid. p. 211.

most of output growth. The early works of Abramovitz (1956), Solow (1957), and Denison (1962) estimated the contribution of this residual to total output growth at 48-52% for the United States in the first half of the 20th century.[2] Successive refinements focused on taking stock of the composition of both physical and human capital (Jorgenson and Griliches 1967, Denison 1985), ascertaining that these dimensions play a fundamental role in understanding economic growth. In Jorgenson and Griliches (1967) the key issue is to accurately include a measure of the quality of the inputs (both capital and labour) in the estimates. This is achieved by disaggregating the total in many different categories: the total factor input then is obtained as a weighted sum of each component, using the corresponding rental and wage rates as weights. Thus, changes in the composition of the inputs lead to changes in the explanatory power of labour and capital, even if the level in physical terms stays the same. Denison (1985) presents a complete overview of these attempts and goes further. Accounting not only for the composition of inputs in terms of intrinsic characteristics, but also for the structural composition, he focuses on the shift over time of workers from low-productivity jobs in farming, for example, to higher productivity occupations in other sectors. This more sophisticated accounting leads him to report a reduction in the residual from 83% to 44% for the growth of output per worker in the US between 1929 and 1982. Yet, the residual remained the single most significant contributor to output growth. Indeed, despite the advances in the statistical methodology, the estimates of the role of the residual for OECD countries between 1960-1995 still hover around 35%.[3]

The conclusion from this discussion is that the factor not explained by the neoclassical growth theory turns out to be the single most important one in statistical decompositions of economic growth. However, the literature on growth accounting has pointed out two fundamental directions for further research: first, by showing how the residual shrinks when taking into account the detailed composition, the sectoral allocation and the increasing quality of human capital (as proxied, for example, by the level of education), it paved the way for the in-depth investigation of the links between growth performance and human capital accumulation; second, given that most economists, following Solow (1957), interpreted the residual as a measure of technological change, the natural conclusion was to focus research on the economics of

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[2] When measured in terms of output per worker, however, these percentages increase considerably averaging around 85%.

[3] See Table 10.1 in Barro and Sala-i-Martin (2004).

technological change.

These tasks were taken on by the new growth literature which changed the focus of the economic analysis of growth towards the explanation of the 'residual', both in terms of technological change (Romer 1986, Romer 1990, Grossman and Helpman 1991, Aghion and Howitt 1992) and of human capital accumulation and education (Lucas 1988). As we will discuss later, along both lines of research, the latest developments have pointed at the necessity of decomposing the relevant aggregate, be it technological knowledge or human capital, into their components, in order to grasp the pervasive effects of compositional issues on final outcomes.

In this work, we refer directly to these latest developments and incorporate the endogenous composition of technology and human capital in the analysis of different problems in environmental, resource and development economics. In the first of the four chapters, we investigate the issue of North-South trade and the pollution haven hypothesis taking into account the incentives for the development of new technologies and the different effects of such technology in the two regions. The second chapter deals with differences in climate policy across countries, their effects on innovation, and the emission of greenhouse gases. The emergence of purely resource-augmenting technical change in capital-resource economies as an equilibrium outcome, constitutes the topic of the third essay; the complex relation between migration of skilled workers, the level of technological development, and the growth performance of developing countries forms the subject matter of the fourth and final one. The rest of this introduction is devoted to a brief presentation of each of them.

DIRECTED TECHNICAL CHANGE AND THE ENVIRONMENT

The first three chapters of this volume are placed within the framework of what is called *Directed Technical Change* (DTC), one of the most recent developments in the field of economic growth. The development of this approach is due to Daron Acemoglu who, building upon the seminal work of Paul Romer (1986, 1990), has addressed the issue of the *direction* and the *bias* of endogenous technological change (e.g. Acemoglu 2002a).

Motivated by the observation that technological change is not neutral in many circumstances, but is rather aimed at benefiting some productive factors above others, Acemoglu has extended previous endogenous growth frameworks to allow for this more realistic feature.[4] In his work, technological

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[4] This observation dates back at least to the formulation of the idea of *induced innovation* by

change is defined as *directed* when it is possible for innovators to decide at which sector to target their innovation efforts. Hence, the amount of R&D directed at specific sectors is driven by the expected profits from a successful innovation in each of them. On the other hand, technological change is *biased* when it increases the marginal product of one of the productive factors more than that of the others. In some sense, thus, the direction of technological change refers to the economic incentives to innovate, while the bias refers to the economic (and technological) consequences of the innovation process. Considering the direction and the bias of technological change provides richer insights into the interactions between the development of new technology and the workings of the economic system in which it occurs. For example, one of the topics where DTC has been usefully applied is the debate on the skill-complementarity of new technologies. Indeed, the puzzling behaviour of the skill premium in the US over the last fifty years has spurred much debate (Katz and Murphy 1992, Galor and Tsiddon 1997b, for example): while the supply of college graduates has increased steadily, the skill premium increased until the early 70's, then decreased throughout the first half of the 80's, and finally soared to reach unprecedented levels with a trend that seems to be still on-going. This pattern can be explained, it has been claimed, by the skill-complementing nature of technical change: that is technical change is, by its own nature skill-biased. This explanation, however, does what neoclassical growth theorists have done for a long time: it simply assumes an exogenous process of technical change to explain an economic phenomenon. Yet, technological change is not skill-complementary by nature as many examples from the eighteenth and nineteenth century confirm.[5] Thus, a solution to the puzzle of the skill premium requires a theory for the direction of technical change. Acemoglu (1998) provides such a theory and shows that the evolution of the skill premium is consistent with a DTC model in which the relative supply of skills (the composition of human capital), determines the relative profitability of new technologies and hence the direction of technical change.

In a long series of papers Acemoglu applies the same type of modelling to other problems in macroeconomics and labour economics.[6] In the first three chapters of the dissertation, we extend the DTC framework, and analyze different topics in environmental economics. We start by addressing the debate on the *Pollution Haven Hypothesis*.

John Hicks (1932).

[5] See, for example, the discussion in Mokyr (1990).

[6] Acemoglu and Zilibotti (2001), Acemoglu (2002a), (2002b), (2003a), and (2003b).

TECHNOLOGY OPTIMISTS VS TRADE PESSIMISTS

The possibility that differences in the stringency of environmental regulation across countries might lead to a relocation of polluting activities to countries with laxer environmental standards constitutes the Pollution Haven Hypothesis. This has been a major point of contention in environmental economics for many years. The natural concern is that international trade would allow rich countries in the North of the world to clean up their environment, at the cost of environmental quality in the poorer countries in the South. The counterargument relies on the fact that technology diffuses internationally: if trade induces the North to specialize in clean production, it might also shift its innovation efforts towards cleaner technologies; once these technologies diffuse to the South, the environment might benefit, overall. In this area, then, the pessimism of trade theorists is opposed to the optimism of technology specialists. In the first chapter of this thesis we analyze the interconnections between international trade, technological change, and environmental regulation and assess the merits of these alternative views.

The chapter focuses on the role of endogenous technological change and technology spill-overs in explaining cross-country differences in pollution, and the pollution haven effect of international trade. We present a North-South trade model with two specific features: first, technology is developed by the North by entrepreneurs who choose the direction of technical change by determining the amount of resources to invest in the development of sector-specific innovations. The technologies that become available then diffuse to the South. Second, environmental regulators in each region choose local environmental policies, by trading off the income gains and the disutility from a rise in pollution.

In the chapter, we argue that the theory of DTC offers new insights in the relationship between international trade and environmental policy. We show that trade may induce the North to develop pollution-saving technologies and the South to reduce pollution, thus reversing traditional reallocation and specialization effects from trade; however, support for technology optimism is not the only possible outcome. If pollution-intensive goods are hard to substitute, an increase in innovation efforts in clean sectors by the North, results in an increased demand for pollution-intensive goods in the South: in this case, trade induces pollution-using technical change, and this induced technology response reinforces the incentive for South to increase pollution. Low substitution thus results in technology pessimism.

We identify two driving forces: on the one hand, the standard terms-of-trade effect tends to induce specialization, and to increase the pollution differential across the two regions. So, when the South is the dirtier region in autarchy, its environmental quality deteriorates with trade. On the other hand, the induced (directed) technological change leads the North to develop pollution-saving technologies, leading to a fall in pollution in the North. However, when technology diffuses to the South, the environment may benefit or not depending on the elasticity of international demand. This ultimately depends on the degree of substitutability among goods. Hence, both a pollution haven outcome, or a virtuous circle of environmental improvements are possible.

Technology diffusion from North to South is, therefore, not necessarily good for the environment in the South, since whether technologies are pollution-using or pollution-saving depends on the profitability of different innovation projects, which in turn depends on comparative advantages and substitutability between goods with different pollution-intensity. By introducing DTC in the analysis, we highlight that, contrary to what is often maintained, technological change is only potentially, not necessarily a blessing.

ASYMMETRIC CLIMATE POLICY AND INNOVATION INCENTIVES

In the second chapter of the dissertation we continue our investigation of DTC in open economies and turn our attention to climate policy, and to the Kyoto Protocol. The Protocol is an international environmental agreement requiring signatory countries to reduce their emissions of green-house gases, mainly carbon-dioxide, over the so-called 'commitment period' 2008-2012. As of July 7, 2006, 164 states and regional economic integration organizations have deposited instruments of ratifications, accessions, approvals or acceptance of the Protocol. Only two of the OECD countries have not ratified the protocol: the Unites States of America and Australia. The chapter focuses on the debate about the effectiveness of the protocol in the presence of large non-ratifying countries. The crux of the argument is that countries outside an environmental agreement may have incentives to increase their emissions, while others are trying to reduce them. This phenomenon is called *carbon leakage*. Such a behaviour on the part of large not ratifying countries could undermine the efforts of the participants, which will find themselves paying the cost of the emissions cut, and at the same time end up without the expected improvement in environmental quality.

Most of the economic literature on the Kyoto Protocol has focused on quantitative evaluations of the degree of carbon leakage in an attempt to evaluate its effectiveness, using large computable general equilibrium (CGE) model. The estimates from these exercises are necessarily sensitive to the widely differing assumptions with respect to the degree of international market integration, substitution and supply elasticities, and market structure found in the literature, as a consequence the leakage rates reported in the literature range from 2% to 130%.

In the chapter we argue that to date the role of technological change has been grossly underestimated in this debate, and develop a two-country framework in which innovations occur endogenously in both regions. We compare the effects of an unilateral emission constraint on the pollution decision in the other country to study the extent of carbon leakage. We show that allowing for endogenous differences in rates of technological change across sectors, that is allowing for DTC, radically changes the perception of the problem. We draw attention to the fact that climate policy, by changing the relative prices (and supplies) of inputs, alters the incentives for innovation. We show that carbon leakage is always reduced in our DTC framework, relative to the un-directed technological change benchmark. Besides, we show that, under particular circumstances, the pattern of carbon leakage may well be reversed, and that the introduction of the Kyoto Protocol might bring about technologies that induce also the non-ratifiers to curb their emissions.

This chapter uses the DTC framework to reach a very important conclusion: it suggests that the pessimism surrounding the Kyoto Protocol might be misplaced, at least as regards emission leakage, and that the available estimates of the effectiveness of the Protocol might be biased downwards.

Directed Technical Change in Capital-Resource Economies

In the third chapter of this volume, we direct our attention to the issue of sustainability, that is to the question whether long-run growth can be sustained in the presence of natural resource scarcity. This topic, as mentioned above, dates back at least to the work of Malthus and Ricardo. In terms of modern economic theory, however, it is the much celebrated *Symposium on the Economics of Exhaustible Resources* of the *Review of Economic Studies* in 1974, to be often recalled as the first close encounter between growth theory and resource economics.

On occasion of the Symposium, the Capital-Resource model of Dasgupta and Heal (1974), Solow (1974), and Stiglitz (1974) was introduced to economics. It is a neoclassical growth model extended to include exhaustible resources as a production factor, and it has since been considered one of the central paradigms in resource economics. More recently, several authors have exploited new growth theories to analyze capital-resource economies with endogenous technical change: see e.g. Barbier (1999), Scholz and Ziemes (1999), Groth and Schou (2002), Grimaud and Rougé (2003), Bretschger and Smulders (2003).

The central aim of both the older and the newer literature is to determine whether, and under what circumstances, technical progress is effective in ensuring sustained consumption. In this regard, the common denominator of both early and recent models is that a strictly positive rate of *resource- augmenting progress* is necessary to obtain non-declining consumption in the long run. In all endogenous growth models with exhaustible resources, ever-increasing consumption *requires* that the resource-augmenting progress strictly exceed the utility discount rate. The same is true for neoclassical models, where the rate of resource-saving progress is exogenous. Hence, most contributions in this field share the view that innovations increase, directly or indirectly, the productivity of natural resources. However, the *existence* of purely resource-augmenting technical progress has not been micro-founded so far. Hence, one may object that the above models are conceptually biased in favor of sustainability: since technological progress may in principle be capital- rather than resource-augmenting these authors may just be making a convenient, but strong assumption.

In the third chapter we investigate whether, and under what circumstances, technical change is endogenously directed towards resource- augmenting innovations. We tackle the issue in a multi-sector DTC framework, where exhaustible resources and accumulable man-made capital are both essential for production.

Our main result is that purely resource-augmenting technical change takes place along the balanced growth path: although the rate of capital-augmenting progress may be positive in the short run, it falls to zero as the economy approaches balanced growth. We thus provide a micro-foundation for Capital-Resource models featuring resource-augmenting progress, in both the Solow-Ramsey and the endogenous technical change frameworks: our results contradict the view that such models are too optimistic with respect to sustainability.

COMPOSITION OF HUMAN CAPITAL AND ECONOMIC DEVELOPMENT

The fourth essay comprised in this thesis takes us away from the field of environmental economics and into the domain of development economics. In this last chapter, we contribute to the debate on the effects of skills' accumulation on growth: we analyze the interaction between the composition of skills, the possibility of migration, and the degree of backwardness of a developing country.

A long tradition, dating back at least to Nelson and Phelps (1966), holds that a larger stock of human capital matters for economic growth. Along these lines are, just to mention a few notable examples, the works of Lucas (1988), Mankiw, Romer, and Weil (1992), and Benhabib and Spiegel (1994). However, more recently, a famous contribution by Krueger and Lindahl (2001) found that the level of education is statistically significantly and positively associated with subsequent growth, only for the countries with the lowest education. As is often the case in economics, this puzzle has spurred a good deal of research on the issue.

A recent paper by de la Fuente and Doménech (2006), has shown that "*these counterintuitive results on human capital and growth can be attributed to deficiencies in the data*" and that "*improvements in data quality lead to larger and more precise estimates of schooling coefficients in growth regressions*".[7] The fact that their 'improvements' in data quality involve the accurate decomposition of educational attainments by level, lends support to our focus on the relevance of composition.

Along the same lines, some recent theoretical contributions have started investigating the role of the composition of human capital. Ramcharan (2004), for example, focuses on the design of optimal educational policy in developing countries, taking into account the effects of different compositions of the human capital stock. He concludes that if the composition of human capital is not taken into account, educational policies may end up promoting the wrong kind of accumulation, thereby leaving the level of development unaffected. Vandenbussche, Aghion, and Meghir (2006), instead, link the effects of exogenous changes in the composition of human capital on growth to the distance from the technological frontier of different countries. In their analysis, changes in the level of human capital have a positive effect. However, depending on the level of the available technology, the composition of the human capital makes a big difference. The closer the economy is to the frontier, the more it will benefit from an increase in the endowment of skilled workers. Conversely, the same economy suffers, and the growth rate decreases, when the share of unskilled workers increases.

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[7] de la Fuente and Doménech (2006), p. 1.

BRAIN DRAIN AND DISTANCE TO FRONTIER

In this chapter, we extend the work of Vandenbussche, Aghion, and Meghir (2006) by allowing for the endogenous accumulation of human capital and by focusing on the distortionary effects of migration in a model which features an out-flow of skilled workers, the so-called *brain drain*. Classical studies of the brain drain suggest that emigration of highly educated people is beneficial for destination countries but harmful for source ones (e.g. Borjas 1994). These conclusions, however, have been challenged by recent contributions which focussed on the potential benefits of the brain drain (for example, Stark, Helmenstein, and Prskawetz 1998, Vidal 1998, Beine, Docquier, and Rapoport 2001). The claim there is that the possibility of emigration induces more skill-creation than skill-loss on balance and that source countries might actually increase their stock of human capital.

Motivated by the largely inconclusive empirical work of Beine, Docquier, and Rapoport (2003), in this chapter we contribute to this debate by focussing on the role played by the *composition* of human capital in fostering productivity growth and, finally, economic development. We argue that not all human capital is *appropriate* for the available technology and the current level of development. In particular, we postulate that the distance to the technological frontier is the key determinant for understanding the effects of human capital accumulation and composition on economic growth. While the accumulation of human capital seems to imply faster technological advancement and economic growth, we point at the different *types* of human capital that are most useful at different stages of development. This view reflects the idea that technological advances become available either through imitation or through innovation, and that each activity requires (a different combination of) different types of skills.

To investigate the distortionary effects of migration on the accumulation of human capital, we model human capital accumulation by agents as an endogenous decision. By letting the type of skills acquired be determined by the costs and benefits faced by heterogenous agents, we add one important dimension to the model. We are in fact able to investigate the interaction between labour market outcomes, migration possibilities and institutional arrangements, such as the existence of educational policies targeted at satisfying the needs of the local economy.

Our results show that the possibility of migration does distort the incentives for agents to accumulate the type of human capital that is appropriate for the country of origin, given its level of development. We show that when migration becomes possible at early stages of economic development the growth rate of the source economy decreases. We also discuss circumstances under which this process leads to development traps, i.e. situations where the process of convergence to the technological frontier stops prematurely.

Finally, we turn to a more normative analysis and show that educational policies, in the form of subsidies to particular types of skills, can counteract the negative effects of migration on growth. Thus, countries wishing to maximize their convergence potential should take this mechanism into account and increasingly subsidize appropriate skills, the further away they are from the technological frontier, and the easier the prospects of migration.

CHAPTER

ONE

TECHNOLOGY OPTIMISTS VS TRADE PESSIMISTS[1]

In the debate on pollution havens, trade pessimists radically disagree with technology optimists.[2] From the perspective of standard trade theory, international goods and investment flows between countries with different environmental standards are likely to concentrate pollution in countries with lax environmental regulations. These countries acquire a (real or apparent) comparative advantage in pollution-intensive activities. The natural concern is that international trade would allow rich countries in the North to clean up their environment at the cost of environmental quality in poorer countries in the South. Opposite to this view is the argument that pollution in different countries is much more technology-driven than trade-driven: while trade liberalization has been important over the last decades, the role of technological change in determining trade patterns and income levels has been at least as important. Technology transfer by multinational firms and the diffusion of clean technologies are often claimed to be a powerful counterbalance to the pollution haven tendencies. When trade induces North to specialize in clean production, it might also shift its innovation efforts to clean technology. If clean technologies diffuse to the South, the environment might benefit.

This chapter formalizes the interconnection between trade, technological change, and environmental regulation. We model two regions which we call

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[1] This chapter is based on Di Maria and Smulders (2004).

[2] For a comprehensive review of this literature see, for example Zarsky (1999). Antweiler, Copeland, and Taylor (2001) and Copeland and Taylor (2004) provide a thorough discussion of the role on international trade on the environment, both from the theoretical and the empirical point of view.

the North and the South. Each region produces two tradable goods, with pollution stemming from only one of them. In both regions local environmental regulators choose environmental policy by trading off the income gains from a rise in pollution against the disutility due to the lower environmental quality. Monopolistic firms in the North invest in new technology to maximize profits. A fraction of these new technologies diffuse to the South since firms there can copy technologies at no cost.

We show that indeed trade may induce the North to develop pollution-saving technologies and the South to reduce pollution, thus reversing traditional reallocation and specialization effects from trade. However, such support for technology optimism is not the only possible outcome. If it is hard to find substitutes for pollution-intensive goods, an increase in innovation efforts by the North in clean sectors results in an increased demand for pollution-intensive goods from the South; in this case, trade induces pollution-using technical change and the induced technology response to trade reinforces the incentive for South to increase pollution. Low substitution thus results in technology pessimism.

Our analysis involves two main steps. First, we study how costs and benefits of environmental policy in the innovating region differ from those in the imitating region. The resulting differences in environmental stringency provide one of the regions with a comparative advantage in pollution-intensive production as a basis for trade. Second, we study whether international trade leads to more or less pollution in the South when the technologies developed in the North diffuse to the South. We identify two effects by which trade affects environmental policy: The conventional *terms of trade effect*, by which trade affects domestic producers' prices and induces them to reallocate production according to comparative advantage; and the *induced technology effect*, which arises since trade affects profits in the two sectors in the North so that innovation effort shifts from one sector to another. This affects the mix of technologies that are available not only in the North, but also - through imitation - in the South.

The existing literature mainly focuses on trade aspects, identifying different sources of comparative advantages. First, if environmental quality is a normal good, increases in the level of income will induce a higher demand for environmental quality. Richer countries will thus tend to have more stringent environmental regulation relative to poorer countries, and to develop a comparative advantage in the production of less polluting goods (see Cole 2004). Second, the comparative advantage for the South in the polluting (resource-intensive) sector may arise as a consequence of ill-defined property rights on the common pool resource (as in Chichilnisky 1994). As South does not regulate access to resources, it over-exploits them, leading to the emergence of an apparent comparative advantage vis-à-vis an otherwise identical country. Finally, comparative advantage in pollution-intensive production may originate from differences in the relative endowments of productive factors (Copeland and Taylor 2003). If capital-intensive goods are also relatively more pollution-intensive, and rich countries are relatively more endowed with capital, they might enjoy a comparative advantage in the pollution-intensive good. This might explain the fact that most production of pollution-intensive goods takes place in developed countries, in spite of their stringent regulation.

We complement this literature with our finding that differences in investment/innovation opportunities and distortions between the innovating North and the imitating South generate a source of comparative advantage in pollution-intensive goods. We isolate this effect by abstracting from the sources of comparative advantage discussed in the previous paragraph. In particular, our assumptions on preferences imply that being richer does not lead *per se* to more stringent environmental policy; we assume that the property rights on the resource base are perfectly defined and enforced; and that the relative factor endowments are identical across regions. Instead, in our setting comparative advantage stems from the difference in enforcement of intellectual property rights in the two regions: the North protects innovators and generates innovation, the South cannot protect innovators and imitates technology from the North.[3]

By almost exclusively relying on trade theory, the theoretical literature on the pollution haven hypothesis seems to have placed insufficient weight on the technology aspects of the debate. Indeed, there is also a small literature that deals with endogenous innovation and pollution havens, e.g. Golombek and Hoel (2005) and Ben Youssef (2003). We differ from these papers in that we do not assume *a priori* that technological change always results in cleaner production. Instead we derive the nature of technological change endogenously from profit incentives (following Acemoglu's (2002a) theory of directed technological change). We also differ from these papers by allowing firms, rather than a planner, to decide on innovation, so that innovation externalities and second-best policies play a role.

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[3] To avoid confusion with the discussion above, notice that here we refer to intellectual property rights protection, while the above discussion referred to the institutional setting regulating ownership of the resource base.

The organization of the chapter is as follows: section 1.1 introduces the model, while section 1.2 discusses the equilibrium. In particular, we address environmental regulation in section 1.2.5. Section 1.3 discusses the pure terms of trade effect by modelling innovation opportunities such that trade induces neither pollution-saving nor pollution-using technical change. Section 1.4 is instead devoted to the analysis of the induced technology effect. Finally, in section 1.5 we collect and compare our main results, and conclude.

1.1 The model

Our economy is made up of two regions, each comprising a set of small countries, which we call the North and the South. These two regions only differ in the institutions regulating intellectual property rights (IPR's) protection. In particular, we assume that IPR's are perfectly enforced in the North, while they are not enforced in the South.

The economy admits a representative consumer who derives utility (U) at each moment in time from produced consumption goods (C) and from environmental quality ($E = \bar{E} - R$), according to the following (intertemporal) CRRA utility function:

$$\int_0^\infty \frac{(C(t)(\bar{E} - R(t))^{\phi})^{1-\varsigma} - 1}{1-\varsigma} e^{-\rho t} dt, \tag{1.1}$$

where ρ is the rate of time preference and ς is the inverse of the intertemporal elasticity of substitution.[4]

Here we view environmental quality as the amount of natural resources ($\bar{E}$) not devoted to productive use (R) at each point in time. We model it as a flow variable, since at every moment in time it returns to its maximum level, $\bar{E}$. Hence, our variable R represents pollution, or more precisely, extractive use of natural resources - clean water and clean air, say - for use in production.

Each consumer maximizes the utility in (1.1) subject to the budget constraint[5]:

$$C + M + D \leq Y \equiv \left(Y_L^{\frac{\varepsilon-1}{\varepsilon}} + Y_R^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}, \tag{1.2}$$

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[4] As is usual in growth theory, the Cobb-Douglas/CRRA structure allows for a balanced growth path with constant environmental quality and a constant rate of growth of consumption. We touch again on this issue on page 27 below. For a complete discussion see Bovenberg and Smulders (1995).

[5] To simplify notation, as long as no confusion arises, we suppress time arguments from now on.

where M is physical investment, and D is the total amount of research and development (R&D) expenditure. The production function in (1.2) shows that final output (Y) is obtained as a CES aggregate of two intermediate goods, Y_R and Y_L, with an elasticity of substitution equal to ε. Moreover expression (1.2) states that consumption, investment and R&D expenditure are all the possible uses of the final good.

The pollution-intensive good (Y_R) is produced using resources and a set of differentiated man-made inputs which we refer to, for simplicity, as "machines", $m_R(j)$. The range of machines that can be used to produce pollution-intensive goods is indicated by N_R. The labour-intensive good (Y_L) is produced using labour and a different set of machines, whose range is N_L. The production functions for the two intermediate goods are:

$$Y_R = \frac{1}{1-\beta}\left(\int_0^{N_R} m_R(j)^{(1-\beta)} dj\right) R^{\beta}, \tag{1.3}$$

and

$$Y_L = \frac{1}{1-\beta}\left(\int_0^{N_L} m_L(j)^{(1-\beta)} dj\right) L^{\beta}. \tag{1.4}$$

For simplicity we have modeled pollution, R, as an input. Stokey (1998) has shown, however, that the Cobb-Douglas specification in (1.3) can be seen as the reduced form of a technology with pollution as an output and abatement possibilities. The key property is that a reduction of marketable output (or an increase in machine inputs) is necessary to cut pollution, either because of a need to save on polluting inputs or because an abatement cost has to be incurred.

Technological change arises from costly innovation: private firms invest in R&D labs in which blueprints for new machine varieties are developed (as in Rivera-Batiz and Romer 1991). Since the R&D stage has to be finished before production of new machines can take place, R&D costs are sunk. As a consequence, only innovators who expect to wield some monopoly power in the future will actually engage in R&D activities. This means that innovation will only take place in the North, where intellectual property rights are protected, while southern producers are able to copy these innovations.

Since R&D generates new blueprints, the total range of machines, N, increases with R&D investments, D. We consider two alternative specifications. In the first, R&D decisions affect the rate at which new blueprints are developed, but innovators cannot know in advance in which of the two sectors their specific innovation will prove most useful. In this case, which we label as "undirected technical change", blueprints in sector *i* expand at the following rate:[6]

$$\dot{N}_i = \frac{\gamma_i D}{(N_R + N_L)^{\psi} / \eta}, \tag{1.5}$$

where D is total R&D investment in the economy and the γ_i is the exogenous probability ($\gamma_R + \gamma_L = 1$) that an individual researcher's effort results in a successful new machine design for sector i. The denominator at the right-hand side of (1.5) represents the "difficulty of R&D" (cf. Segerstrom (1998)), which depends on two opposing effects. On the one hand, we assume that the more innovations in any sector already have been generated, the harder it is to come up with the next innovation. We capture this by the factor $(N_R + N_L)^{\psi}$, where $\psi > 0$. On the other hand, new innovation opportunities may arise exogenously over time. This can be viewed as reflecting any kind of innovation not driven by sector-specific profit incentives. We capture the level of innovation opportunities by parameter η, which we assume to grow at an exogenous rate ψg.[7]

In our second specification of innovation possibilities, technical change is directed, following Acemoglu (2002a), so that innovators can target their efforts at a specific sector, and blueprints in sector *i* expand at the following rate:

$$\dot{N}_i = \frac{D_i}{(N_R + N_L)^{\psi} / \eta}. \tag{1.6}$$

While the denominator is the same and motivated by the same arguments as in (1.5), the rate of innovation in each sector depends on the total R&D effort taking place in it, D_i, with $D_L + D_R = D$.

Although we think the directed technical change variant is more realistic, contrasting undirected to directed technical change allows us to disentangle the terms of trade effect and the induced technology effect.

Finally, we assume that labour supply is exogenously fixed at L, while the environmental regulator in each country puts an endogenously determined cap on pollution R.

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[6] Throughout the chapter dotted variables indicate time derivatives, that is $\dot{x} = dx/dt$.

[7] Assuming $\psi = 0$, we would have an endogenous growth model, in which the long-run growth rate is endogenous. Although generating very similar results, the fully endogenous growth version of this model involves a more complicated analysis so that we ignore it here.

1.2 Equilibrium

Firms maximize profits and households maximize utility. They all take as given prices and factor rewards, with one notable exception: producers of machines in the North can set their own price as they operate under monopolistic conditions. Finally the environmental regulator in each country maximizes the utility of the representative agent by choosing the nation-wide level of pollution (resource supply), taking as given international prices. All markets clear and the resource constraint is satisfied. The final good is chosen as the numeraire.

In what follows we only focus on the long-run balanced growth path of this economy, where prices and the amount of natural resources used in production are constant and where output, consumption, investment and R&D outlays, as well as N_R and N_L, all grow at the (exogenous) rate g.[8]

1.2.1 Intermediate goods and machines

We start from the production of intermediate goods. To simplify the exposition, we let $S_R \equiv R$ and $S_L \equiv L$. Firms that employ factor i ($i = L, R$) maximize their profits choosing the amount of factor S_i to employ and the amount of machines $m_i(j)$ of each type to use. Their maximization problem is then:

$$\max_{S_i, \{m_i(j)\}} p_i Y_i - w_i S_i - \int_0^{N_i} p_{m_i}(j) m_i(j) dj, \tag{1.7}$$

subject to the production functions (1.3) and (2.3), and taking as given both goods' and factors' prices.[9] The demands for machines resulting from the above maximization are:

$$m_i(j) = \left(\frac{p_i}{p_{m_i}(j)}\right)^{\frac{1}{\beta}} S_i. \tag{1.8}$$

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[8] With constant factor supply R and L, the constant returns to scale production functions (1.2)-2.3 imply that output grows at the same rate as N_R and N_L. The goods market equilibrium condition (1.2), moreover, requires Y, C, M and D to grow at a common rate. The innovation functions (1.5) and (1.6) imply that the growth rate of N_i can be constant only if $(N_R + N_L)^{\psi} / \eta$ is constant (see Jones 1995). Hence, the growth rate of this economy equals $(\dot{N}_i / N_i) = (\dot{\eta}/\eta)\psi = g$. Given the choice of the final good as numeraire, prices are constant along the balanced growth path.

[9] For simplicity, we assume that machines depreciate fully after use. As discussed by Acemoglu (2002a), assuming slow depreciation of machinery would not change the balanced growth equilibrium path.

Consider first the supply of machines in the North. Since intellectual property rights are perfectly enforced, ownership of blueprints allow northern producers to act as monopolists. Assuming that v units of the final good are required to produce each machine and that machine production is subsidized at rate τ_m, the expression for the profits of a monopolist supplying the i-complementary machine j is given by $\pi_i(j) = (p_{m_i}(j) - v(1-\tau_m))\, m_i(j)$, $j \in (0, N_i]$. Given the demand function in (1.8), the profit-maximizing price will be set as a mark-up over marginal cost, and will equal $p_{m_i}(j) = v(1-\tau_m)/(1-\beta)$. To simplify the algebra, we assume v to be equal to $1-\beta$, so that $p_{m_i}(j) = (1-\tau_m)$. Substituting for machine prices and demand functions in the expressions for the profits of the technology monopolist, one gets:

$$\pi_i(j) = (1-\tau_m)^{-(1-\beta)/\beta} \beta p_i^{1/\beta} S_i. \tag{1.9}$$

Using machine demands (1.8) and prices in the sectorial production functions (1.3) and (2.3), we obtain the supply functions for northern firms, that we identify with an n superscript:

$$Y_i^n = \left(\frac{1}{1-\beta}\right)^{1/\beta} \left(\frac{1-\beta}{1-\tau_m}\right)^{(1-\beta)/\beta} (p_i^n)^{(1-\beta)/\beta} N_i^n S_i^n. \tag{1.10}$$

Next, turn to the South. IPR's are not enforced in the South, patent protection is not effective and the sunk costs associated with the development of new blueprints cannot be recouped. This effectively rules out the possibility that a local R&D sector may arise in the South. We assume, though, that southern producers can copy at no cost blueprints developed in the North. In particular, a fraction $\delta \in (0,1)$ of the blueprints from North becomes available in the South, so that

$$N_i^s = \delta N_i^n.$$

Diffusion is incomplete due to a time lag between innovation and imitation, or because some blueprints are inherently too complex (and thus too costly) to copy.

As no institutional arrangement protects the monopoly power of machine producers, and no sunk costs prevent copying by more than one producer, perfectly competitive markets ensue. The price of machines in the South will then equal marginal cost: $p_{m_i}(j) = (1-\beta)$. Substituting machine demands (1.8) and prices into the sectorial production functions (1.3) and (2.3), we obtain:

$$Y_i^s = \left(\frac{1}{1-\beta}\right)^{1/\beta} (p_i^s)^{(1-\beta)/\beta} \delta N_i^n S_i^s. \tag{1.11}$$

Comparing (1.11) and (1.10), we see that for $\delta < ((1-\beta)/(1-\tau_m))^{(1-\beta)/\beta}$, productivity (per unit of factor S_i) is lower in the South than in the North, so that the diffusion parameter δ realistically allows the South to be poorer than the North.

1.2.2 Final goods and the production elasticity of pollution

Final goods' producers demand intermediate goods up to the point where marginal productivity equals price. This implies $\partial Y/\partial Y_i = p_i$, which from (1.2) implies the following relative demand for intermediate goods:

$$\frac{p_R}{p_L} = \left(\frac{Y_R}{Y_L}\right)^{-\frac{1}{\varepsilon}}, \tag{1.12}$$

where Y_i represents the demand for intermediate good i.

In the rest of the analysis, the production elasticity of polluting inputs will play a central role. We can write this elasticity as

$$\frac{\partial Y}{\partial R}\frac{R}{Y} = \beta\theta_R = \beta\frac{p_R Y_R}{Y}, \tag{1.13}$$

where we made use of (1.3) to write $(\partial Y_R/\partial R)(R/Y_R) = \beta$ and we introduced the production elasticity (and cost share) of pollution-intensive goods in final goods production, $\theta_R \equiv (\partial Y/\partial Y_R)(Y_R/Y) = p_R Y_R/Y$. Since the production elasticity of pollution and θ_R move together for any given β, we will find it easier to refer to the latter in the discussion that follows. Moreover, note that since (1.2) features constant returns to scale, $1-\theta_R = p_L Y_L/Y$. Using (1.10) or (1.11), we can express the relative costs share $p_R Y_R/p_L Y_L$ in each region as:

$$\frac{\theta_R}{1-\theta_R} = \left(\frac{p_R}{p_L}\right)^{1/\beta}\frac{N_R R}{N_L L}. \tag{1.14}$$

This reveals that the share of pollution-intensive goods in production, θ_R, depends on relative prices, relative factor supply, and technology.

1.2.3 R&D and innovation

Firms in the North have an incentive to innovate whenever innovation earns a rate of return that is at least equal to the market interest rate. This implies the following arbitrage equation for innovator j:

$$\frac{\tilde{\pi}_j}{v_j} + \frac{\dot{v}_j}{v_j} = r \tag{1.15}$$

where $\tilde{\pi}_j$ is the per period flow of expected revenues (dividends) for the holder of a blueprint j, v_j is the market value of blueprint j, and r is the interest rate. In the model of undirected technical change, expected dividends equal $\tilde{\pi}_j = \gamma_R \pi_R + \gamma_L \pi_L$; in the model of directed technological change they equal $\tilde{\pi}_j = \pi_i$ if j's effort is directed to sector $i = R, L$.

We assume free entry in research activities, which implies that the value of a blueprint cannot exceed its cost. From (1.5) and (1.6), this implies $v_j \leq (N_R + N_L)^{\psi}/\eta$. In particular, in the undirected technical change model, this condition must hold with equality whenever innovation occurs, that is whenever $D > 0$; in the directed technical change model it holds with equality for $j = i$, where $i = R, L$ is the sector in which innovation takes place ($\dot{N}_i > 0$).

In the undirected technical change model, the long-run ratio N_R/N_L equals γ_R/γ_L, as follows from (1.5). Hence, the relative supply of machine variety only depends on research technology and cannot be affected by e.g. trade. Once in a balanced growth path, only shocks to N_i or γ_i can bring the economy from its balanced growth path. This allows us to treat N_R/N_L as a constant in the undirected technical change model.

In the directed technical change model, along the balanced growth path innovation takes place in both sectors, the cost and value of a blueprint is the same in both sectors ($v_R = v_L$) and to satisfy the condition (1.15), we must have $\pi_R = \pi_L$. After substitution of (2.18), this implies the following "no-arbitrage" condition:

$$\left(\frac{p_R}{p_L}\right)^{1/\beta} \frac{R}{L} = 1. \tag{1.16}$$

The relative profitability of innovations in each sector thus increases with the price of the intermediate good they are used to produce (the price effect), and with the relative supply of the factor they complement (the market-size effect).

1.2.4 Households

Households maximize their lifetime utility (1.1), subject to the usual intertemporal budget constraint. This results in the Keynes-Ramsey rule stating that consumption grows at a rate proportional to the difference between the interest rate and consumer's rate of time preference.

Along the balanced growth path, consumption and output grow at the same rate, g, so that we may express this equation as:

$$r = \rho + \varsigma g. \tag{1.17}$$

1.2.5 Environmental regulation

We assume that the environmental regulator determines the level of pollution in the economy.[10] We model the regulator assuming that she only aims at correcting the environmental externality from production mentioned above. She chooses the supply of pollution to maximize the utility of the representative agent at each moment in time, taking as given the choices made by the other economic agents in the economy, concerning the level of consumption and of investment in both machines and R&D.

To gain some intuition, we first derive the environmental policy rule in general terms. As in a static context, the maximization of $U(C, \bar{E} - R)$ subject to a budget constraint of the form $C = F(R, \cdot\,) - D - M$, where D and M are the (given) amounts of investment in R&D and in machines, yields the following first-order condition

$$\left(\frac{\partial U}{\partial C}\right)\frac{\partial Y}{\partial R} - \left(\frac{\partial U}{\partial E}\right) = 0,$$

that we can rewrite, in terms of elasticities, as

$$\left(\frac{\partial Y}{\partial R}\frac{R}{Y}\right)\frac{Y}{C} = \left(\frac{(\partial U/\partial E)E}{(\partial U/\partial C)C}\right)\frac{R}{\bar{E} - R}. \tag{1.18}$$

This equation balances the marginal benefits from pollution (in the form of additional consumption goods) and its marginal costs (in the form of lower environmental amenities), both measured in terms of consumption.

Equation (1.18) also shows how the supply of pollution depends, all other things equal, on the production elasticity of polluting inputs, on the consumption to output ratio, and, finally, on the share of environmental amenities in utility. First, a higher production elasticity of resources, $\left(\frac{\partial Y}{\partial R}\frac{R}{Y}\right)$, makes resources more valuable in production and increases the marginal benefits of pollution. In other words, the costs of reducing pollution become larger, or, equivalently, the opportunity cost of environmental policy increases. Second, a lower consumption to output ratio C/Y increases the equilibrium supply of pollution by increasing its marginal benefits. Intuitively, in an economy with lower consumption per unit of output consumption is perceived as relatively scarce, thus the marginal value of production relative to the marginal value of environmental quality is increased. Finally, a higher share of amenities in utility, $\frac{(\partial U/\partial E)E}{(\partial U/\partial C)C}$, increases the marginal benefits of environmental quality (i.e. it increases the marginal costs of pollution), shifts the MC curve up, and hence decreases equilibrium pollution.

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[10] We also assume that environmental policy is perfectly enforced in both regions.

We can rewrite (1.18) noting that the share of environmental amenities equals ϕ, see (1.1), and that the production elasticity of pollution is given in (1.13). This yields the following expression for the marginal benefits and the marginal costs of pollution:

$$\underbrace{\frac{\theta_R \beta}{C/Y}}_{MB} = \underbrace{\phi \frac{R/L}{\overline{E}/L - R/L}}_{MC}. \tag{1.19}$$

Rearranging terms and subtracting R/L to both sides of the previous equation we obtain,

$$\left(\frac{\beta}{\phi C/Y}\right)\frac{\overline{E}}{L} - \left(\frac{\beta}{\phi C/Y} + 1\right)\frac{R}{L} = \left(\frac{1-\theta_R}{\theta_R}\right)\frac{R}{L},$$

that we can rewrite, using (1.14), and letting $\frac{\beta}{\phi C/Y} = \Omega$,[11] as:

$$\Omega\,\frac{\overline{E}}{L} - (\Omega + 1)\,\frac{R}{L} = \left(\frac{p_R}{p_L}\right)^{-1/\beta}\left(\frac{N_R}{N_L}\right)^{-1}. \tag{1.20}$$

This expression will prove more tractable in the analysis that follows than (1.19), bear in mind, however, that this condition still states that pollution will be set at a level that equals marginal benefits to marginal costs. We will use this expression to determine the level of pollution chosen by each region's regulator under autarchy and under free trade, and to discuss how these decisions will be influenced by the directedness of technical change.

In the introduction, we pointed out that our model rules out international differences in environmental policy due to differences in income, factor endowments, or resource property right regimes. We do so in order to isolate the effect of endogenous technology from other mechanisms explaining pollution haven effects in the existing literature. Equation (1.20) reveals how we do this. First, if output and consumption grow at the same rate, $\Omega \equiv \beta/(\phi C/Y)$ is constant. Then, the equilibrium supply of pollution must be the same for each level of income. This is due to the Cobb-Douglas specification of the utility function (1.1), which implies that the larger demand for environmental quality due to higher income is exactly offset by the higher cost of pollution reduction generated by the increasing productivity of polluting inputs which drives growth. Second, we assume that relative factor endowments, $\bar{E}/L$, and preferences, reflected by ϕ, are the same in both regions. This leaves us with

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[11] It is important for the analysis that follows to bear in mind that Ω is a constant along the balanced growth path in each country. Yet, its value depends on the country specific level of C/Y. Thus, a country with more consumption per unit of final output, will have a lower Ω.

three determinants for the differences in R/L, as shown in equation (1.20): differences in the consumption-to-output ratio across countries, prices, and technology.[12]

In the next section we discuss the differences in the C/Y ratios between North and South. We will show that they do not depend either on the trade regime, or on the assumptions concerning the innovation process. With this in mind, we can explain the different outcomes of the model under the different trade regimes in terms of price and technology effects only.

In the remainder of the chapter we will be able to separate price and technology effects since we will first focus on undirected technological change - in which case the bias N_R/N_L is exogenous - and later on directed technological change - with the bias N_R/N_L endogenously determined. For each technology regime, moreover, we will discuss and compare autarchy, where prices differ across countries, and free trade, where price equalization obtains.

1.2.6 The consumption to output ratio

As mentioned above, the consumption to output ratio constitutes one of the central elements of our analysis. Here we provide an expression for this ratio in each country that we can use to substitute in expression (1.20). Appendix A shows that the the C/Y ratio in the South is

$$\left(\frac{C}{Y}\right)^s = 1-(1-\beta)=\beta, \tag{1.21}$$

while its northern homologue is

$$\left(\frac{C}{Y}\right)^n = 1-(1-\beta)\left(\frac{1-\beta}{1-\tau_m}\right)-(1-\beta)\beta\frac{g}{r}. \tag{1.22}$$

Comparing the two expressions above, we note two differences. First, the North will invest less in physical capital, since northern producers of intermediate goods face higher machine prices than their southern counterparts. Indeed, in the North monopolistic competition, fostered by IPR's enforcement, drives prices above marginal cost, while this cannot happen in the South were patent protection is not enforced. This first effect is reflected by the second

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[12] From (1.20), it is straightforward to see that our analysis using the C/Y ratios, can be alternatively carried out through differences in ϕ and $\overline{E}/L$. As long as North has higher ϕ and/or lower $\overline{E}/L$, the analysis is qualitatively similar to the analysis that follows where the North has an higher C/Y ratio than the South.

term on the right-hand side of (1.22). As long as the monopolistic distortion is not off-set by an appropriate subsidy ($\tau_m = \beta$), the North will spend less for machines than the South. Second, the North consumes less than the South out of its gross output, since part of it is invested in developing new technology (research expenditures, the third term at the right-hand side of the equation above). Northern innovators find it profitable to forego some consumption in order to invest in R&D, whereas this is impossible for southern (potential) innovators. It is clear that these two effect work in opposite direction and that, depending on the level of the subsidy, any of the two can dominate. In particular, it is easy to show that $(C/Y)^n > (C/Y)^s$ whenever $\tau_m < \frac{\beta(r-g)}{r-g\beta}$.

1.3 Undirected Technical Change

In this section we analyze the pollution supply by the two regions assuming that innovators cannot change the long-run composition of technology N_R/N_L. We analyze both the autarchy case, where the only interdependence between the two regions stems from the international diffusion of technology, and the free trade situation. In this context the only effect of trade is through changes in prices. This section will provide us with a benchmark for the analysis of the directed technical change case, in the following section.

1.3.1 Autarchy

Under autarchy, domestic relative demand for final goods equals domestic supply. Substituting supply (1.10) or (1.11) into the expression for demand (1.12), we find that the domestic price ratio is given by the following function of relative factor supply and technology:

$$\frac{p_R}{p_L} = \left(\frac{N_R R}{N_L L}\right)^{-\beta/\sigma}, \tag{1.23}$$

where $\sigma = 1 + (\varepsilon - 1)\beta$ is the elasticity of substitution between R and L in aggregate production. Substituting this into (1.20), we obtain the following expression that determines pollution supply under autarchy:

$$\Omega\frac{\overline{E}}{L} - (\Omega + 1)\frac{R}{L} = \left(\frac{N_R}{N_L}\right)^{\frac{1-\sigma}{\sigma}} \left(\frac{R}{L}\right)^{\frac{1}{\sigma}}. \tag{1.24}$$

We have thus obtained a (relatively) simple equation in the relative factor supply only. We note that $\overline{E}/L$, N_R/N_L, and σ are the same across countries, while

Ω differs. Recalling that $\Omega = \beta/(\phi C/Y)$, it is straightforward to see that the region with the highest C/Y has the lowest Ω, and thus chooses the lowest R/L, according to (1.24).

Since a closed form solution cannot be obtained analytically, we derive further results graphically. The left-hand side of the equation above is linear in pollution supply and negatively sloped, while the right-hand side is an increasing function of R/L with a curvature which depends on σ. We plot the left- and the right-hand sides of (1.24) in figure 1.1 below, as LHS and RHS, aut, respectively.[13] The solid lines describe the situation under autarchy.

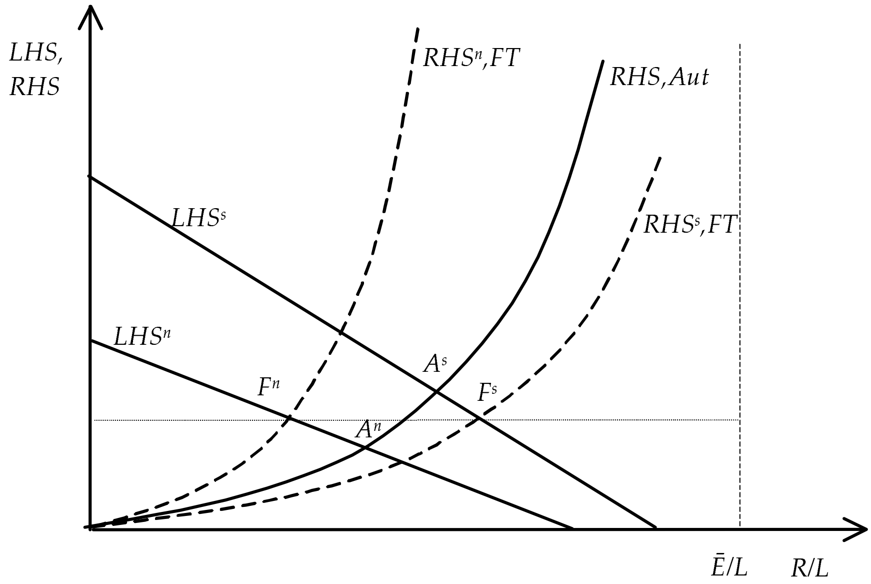

Figure 1.1: *Equilibrium with Undirected Technical Change under Autarchy and Free Trade*

It is easy to see from (1.24) that the line depicting the left-hand side will be steeper and further to the North-East, the larger Ω, that is the smaller the consumption to output ratio. In the picture we depicted the situation in which the North has the largest C/Y and thus the lowest line. The right-hand side is shared by the two countries, so that the equilibrium will obtain at a point characterized by less pollution in the North than in the South.

Intuitively, the reason for this result lies in the difference in the marginal benefits from pollution. Remembering the first-order condition in (1.19), it is

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[13] The figure is drawn for the case where $\sigma < 1$. The curves depicting the right-hand side would be concave for $\sigma > 1$, but qualitatively nothing would change in our analysis.

immediate to see that, while the marginal cost term (on the right-hand side) is the same for every country, the marginal benefit term (on the left-hand side) depends negatively, *ceteris paribus*, on the C/Y ratio. Loosely speaking, the more consumption each country obtains out of any unit of output, the lower the marginal benefit (in terms of consumption) it derives from any marginal increase in pollution.

1.3.2 International trade

Once goods are traded internationally without frictions, one single price p_i^w for each good $i = R, L$ will prevail at the world level. This implies that the right-hand side of (1.20) is the same across countries. Equating the left-hand side of (1.20) for both regions, and rearranging, we find:

$$\frac{R^s}{L^s} = \frac{R^n}{L^n} + \left(\frac{\Omega^s - \Omega^n}{1 + \Omega^s}\right)\left(\frac{\overline{E}}{L} - \frac{R^n}{L^n}\right), \tag{1.25}$$

This shows that, as long as $\Omega^s > \Omega^n$ (that is as long as $(C/Y)^s < (C/Y)^n$), the South will pollute more than the North also under free trade. More generally, we can conclude that countries that consume relatively less tend to impose laxer environmental regulation and hence to pollute more. From now on we state that $\Omega^s > \Omega^n$ corresponds to a situation in which South has a comparative advantage in polluting goods (if $\Omega^n > \Omega^s$, the North has it).

When international trade is allowed, the equilibrium world relative price is determined by the market clearing condition on the world markets, that is, from (1.12) and relative supply: $(p_R/p_L)^{-\varepsilon} = (Y_R^n + Y_R^s)/(Y_L^n + Y_L^s)$.

Substituting (1.10) and (1.11), we find the following solution for the world relative price:

$$\frac{p_R}{p_L} = \left(\frac{N_R}{N_L}\left[\lambda^n \frac{R^s}{L^s} + \lambda^s \frac{R^s}{L^s}\right]\right)^{-\frac{\beta}{\sigma}}, \tag{1.26}$$

where $\lambda^n = 1 - \lambda^s = [1 + (\frac{1-\tau_m}{1-\beta})^{(1-\beta)/\beta}\delta L^s/L^n]^{-1}$. The term in the brackets on the right-hand side in (1.26) is the world supply of pollution relative to labour, in efficiency terms, written as a weighted average of the national relative factor supplies R^n/L^n and R^s/L^s.

By substituting (1.26) and (1.25) into (1.20), we find:

$$\Omega^n \frac{\overline{E}}{L} - (\Omega^n + 1)\frac{R^n}{L^n} = \left(\frac{N_R}{N_L}\right)^{\frac{1-\sigma}{\sigma}} \left[\frac{R^n}{L^n} + \lambda^s \frac{\Omega^s - \Omega^n}{1 + \Omega^s}\left(\frac{\overline{E}}{L} - \frac{R^n}{L^n}\right)\right]^{\frac{1}{\sigma}}. \tag{1.27}$$

By interchanging the s and n superscripts we get the condition that determines equilibrium pollution in the South. To understand the effect of free trade when technical change is undirected, we need to compare this expression with the corresponding one for autarchy, (1.24). We do this using once more a graphical treatment for clarity. First of all, we notice that the left-hand side does not change, so that the relevant curves are still the solid downward sloping lines in figure 1.1. As for the right hand side, all else equal it will be below the corresponding autarchy curve whenever the own country's Ω is larger than the foreign one. Assuming once more that the North consumes relatively more than the South, this means that the northern curve will shift up, while the southern one will shift down, relative to autarchy. This is represented by the two dotted lines in of figure 1.1. [14]

North and South are interdependent through goods trade and diffusion of technology from North to South. The literature on international technology diffusion argues that the two are connected: international communication and contacts stimulate technology spillovers, e.g. (Keller 2004). We therefore now study how our results depend on our parameter for technology diffusion, δ. An increase in δ, the fraction of northern technologies copied in the South, raises production levels in the South, see (1.11). In autarchy, this raises aggregate production without changing relative variables. In particular, the equilibrium pollution labour ratio is independent of δ, see (1.20). In free trade, the increased supply from the South affects the world price: if the South has a comparative advantage in pollution-intensive goods ($\Omega^s > \Omega^n$), the world relative supply of these goods increases with δ (for given relative factor supplies in the regions) and their relative price falls. This lower price for polluting goods makes it less attractive for both countries to pollute. Indeed, in (1.27) an increase in diffusion parameter δ lowers λ^n and increases λ^s so that the dashed curves in figure 1.1 shift up and both regions pollute less. A change in δ, however, can never reverse our finding that the country with comparative advantage in pollution-intensive goods pollutes more in free trade than in autarchy; this result holds for any $0 < \lambda^n = 1 - \lambda^s < 1$ and hence for any δ, see (1.27).

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[14] To construct the diagram in figure 1.1, it would be sufficient to draw only one of the dotted lines. As noted above, with international price equalization, the right-hand side of (1.20) must be the same for every country, in equilibrium. Thus both crossing points F^n and F^s will lie on the same horizontal line, as drawn in the figure above. We will make use of this in the next section.

1.4 Directed Technical Change

When innovators can direct innovation at a particular sector, the nature of technological change becomes endogenous and responds to shocks, for example to changes in international prices. International trade thus naturally affects environmental policy in both regions, not only directly through prices, but also indirectly, through the induced changes in technology. Furthermore, even when there is no international trade in goods, innovation in the North affects technology and environmental policy in the South, through the international diffusion of northern technologies.

1.4.1 Pollution-using vs pollution-saving technical change

Under directed technical change, international trade endogenously induces either pollution-using or pollution-saving technical change, in this subsection we provide a definition for these concepts.

If innovation occurs at a faster pace in one of the sectors, the N_R/N_L ratio changes. The effect of this change on the composition of production in the long run depends on the elasticity of substitution between factors of production, σ. In general, a change in the composition of technology affects the production elasticity of pollution. This either increases or reduces the cost of pollution reduction in terms of output, i.e. the cost of abatement. When this elasticity increases, the marginal benefits from pollution increase and thus the supply of pollution will increase in equilibrium, recall (1.18). We call this kind of technical change *pollution-using*. The opposite occurs when the elasticity decreases, making pollution reduction less costly. In this case we speak about *pollution-saving* technical change. The two concepts correspond to higher and lower abatement costs, respectively. An inspection of equations (1.24) and (1.27) shows that the right-hand side of both expressions increases with $(N_R/N_L)^{(1-\sigma)/\sigma}$. We can interpret this as showing that an increase in this term, which we label the technology bias, represents pollution-saving technical change.

We can make this point more formal recalling, from our discussion in section 1.2.2, that we can proxy the production elasticity of pollution by the cost share of polluting goods θ_R. Using equation (1.14) and substituting the autarchy prices from (1.23), for example, we get

$$\frac{\theta_R}{1-\theta_R} = \left(\frac{N_R}{N_L}\right)^{-\frac{1-\sigma}{\sigma}} \left(\frac{R}{L}\right)^{-\frac{1-\sigma}{\sigma}}, \tag{1.28}$$

which clearly shows that, when the technology bias $(N_R/N_L)^{(1-\sigma)/\sigma}$ increases, the cost share θ_R falls for given factor supply, which implies pollution-saving technical change.[15] This also shows that the nature of technical change not only depends on the direction (the change in N_R/N_L) but also on the elasticity σ. For example if firms in the pollution-intensive sector innovate more than in the other sector, the ratio N_R/N_L increases. Whether this raises or reduces the production elasticity of pollution, depends of the elasticity of substitution σ . If the two goods are gross substitutes ($\sigma > 1$), the relatively fast productivity improvements in the pollution-intensive sector induce a shift towards this sector and technological change is pollution-using. If however gross complementarity applies ($\sigma < 1$), the same productivity improvements trigger a relative increase in the demand for the complementary input and technological change is labour-using, and hence pollution-saving.

1.4.2 Autarchy

The long-run technology bias is determined in the North by the condition that the profits from innovation are equal across sectors, that is from the no-arbitrage equation derived in section 1.2.3. We first focus on autarchy, finding the following expression for the technological differences across sectors using (1.16) and (1.23):

$$\left(\frac{N_R}{N_L}\right)^{\frac{1-\sigma}{\sigma}} = \left(\frac{R^n}{L^n}\right)^{-\frac{(1-\sigma)^2}{\sigma}} . \tag{1.29}$$

This equation shows that under autarchy the bias of technology in both regions depends only on pollution policy in the North, R^n/L^n. Moreover, we can immediately see that a decrease in the relative supply of pollution results in pollution-saving technological change. Hence, the more stringent the environmental policy in the North, the more pollution-saving technological change.

To determine equilibrium pollution supply under autarchy, we can substitute the long-run bias derived above into the environmental policy rule (1.24). The expression differs across countries. For the North the equilibrium condi-

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[15] The corresponding expression for θ_R under free trade is obtained by substitution of the international prices from (1.26). Also in the resulting expression θ_R decreases with $(N_R/N_L)^{(1-\sigma)/\sigma}$ for given factor supply. Our classification is thus independent of the trade regime.

tion reads:

$$\Omega^n \frac{\overline{E}}{L} - (\Omega^n + 1) \frac{R^n}{L^n} = \left(\frac{R^n}{L^n} \right)^{2-\sigma}, \tag{1.30}$$

while for the South we get,

$$\Omega^s \frac{\overline{E}}{L} - (\Omega^s + 1) \frac{R^s}{L^s} = \left(\frac{R^n}{L^n} \right)^{2-\sigma} \left(\frac{R^s/L^s}{R^n/L^n} \right)^{1/\sigma}. \tag{1.31}$$

In figure 1.2 we construct a diagram analogous to the previous one, to illustrate the situation in this case. Once again, we indicate the curves that are relevant for the discussion of the autarchy case with solid lines.

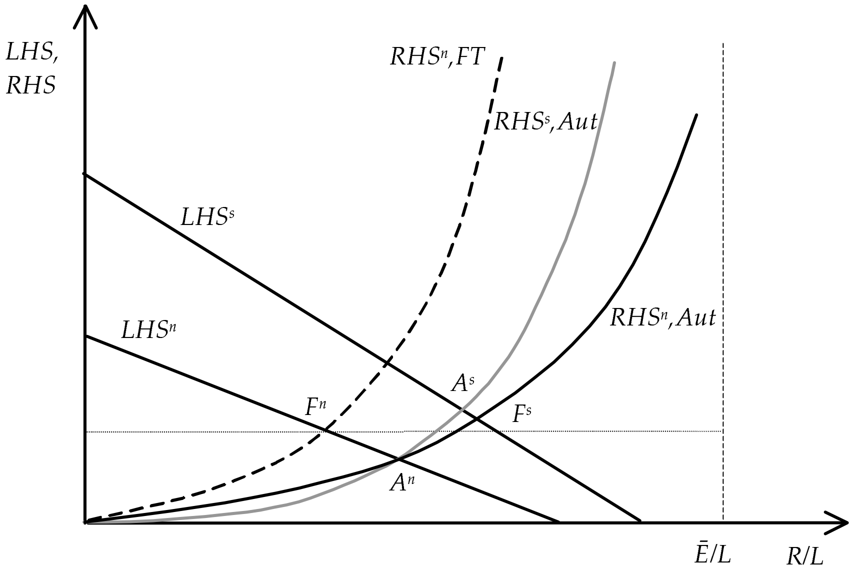

Figure 1.2: *Equilibrium under Directed Technical Change under Autarchy and Free Trade*

We start from the curves for the North. The curve that depicts the left-hand side is identical to the straight line we drew in figure 1.1. The right-hand side is increasing for $\sigma < 2$ and decreasing for $\sigma > 2$. In the picture we depict the case where $\sigma < 1$ and $\Omega^n < \Omega^s$. The intersection point A^n represents the equilibrium for the North.[16] We can use the corresponding value of R^n/L^n

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[16] As long as $\sigma \leq 2$ this equilibrium always exists and is unique. When $\sigma > 2$, the line describing the right-hand side is decreasing and convex, it can intersect the straight line either once, twice, or never. When multiple crossings occur, we must rule out the intersection at which *RHS* cuts *LHS* from above, since starting from such a point, slightly increasing pol-

to construct the curve for the South. This curve intersects the northern one at A^n, and is drawn as the lighter curve in the figure. Point A^s represents the equilibrium for the South.

This picture enables us to draw some conclusions for the autarchy case. In the first place, we notice that, as in the undirected technical change case, also here the country with the highest Ω will pollute more. In this sense the regime of technical progress does not influence the outcome. As long as the North enjoys a higher C/Y ratio, it will choose a lower equilibrium level of pollution than the South.

Second, comparing equations (1.24) and (1.30), we immediately conclude that the line depicting the right-hand side for the North is steeper under undirected technical change than under directed technical change. This has the important consequence that any shock (such as changes in Ω via preferences or subsidies, or in relative endowments, $\overline{E}/L$) has a larger impact on pollution supply under directed technical change than under undirected technical change. Intuitively, this happens because under directed technical change the adjustment occurs not only through policy but also through changes in the composition of technology. For example, assume that preferences become greener (ϕ increases), this leads to the adoption of more stringent environmental policy and to a reduction in pollution supply. Under directed technical change this leads firms to develop pollution-saving technologies, which would have not occurred had technical change been undirected, and thus to curb pollution further.

Third, shocks in the North affect the South even without international trade in goods, through the international technology spillovers. Indeed, once a shock hits the North both pollution and technology adjust. Technology diffusion will then induce the South to modify its pollution decisions according to the new available technology. This means, for example, that the South will benefit from pollution-saving technical change that occurs in the North following a tightening in the stance of environmental policy.

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lution supply rises marginal benefits relative to marginal costs to pollution. In other words, second order conditions are violated. Moreover, the case of no intersection is not of interest to our discussion, as it implies a corner solution in which both regions produce with zero pollution in the long run. In the rest of the chapter we thus focus on interior solutions, which can always be constructed by choosing low enough a value for ϕ.

1.4.3 International trade

When technical change is directed, the effects of a liberalization in international trade are twofold. First, price changes affect pollution supply through the traditional terms-of-trade mechanism as with undirected technological change. Second, price changes now also affect the direction of technological change. In this section we will show that, while the terms-of-trade effect tends to increase differences in pollution supply, the effects of changes in technology can either exacerbate or dampen this tendency. In particular, we show that the effect of the induced technical change may prove strong enough for the non-innovating country to reverse the terms-of-trade effect. Thus, provided that factors of production are sufficiently good substitutes, both regions might end up changing their environmental policy in the same direction.

As in the previous section, we get the long-run technology bias from the no-arbitrage condition (1.16), but we now use (1.26) to substitute for prices. This yields:

$$\left(\frac{N_R}{N_L}\right)^{\frac{1-\sigma}{\sigma}} = \left(\frac{R^n}{L^n}\right)^{1-\sigma} \left[\lambda^n \frac{R^n}{L^n} + \lambda^s \frac{R^s}{L^s}\right]^{-\frac{1-\sigma}{\sigma}} . \tag{1.32}$$

This equation shows that changes in the relative factor supply affect the bias of technological change through two terms: $(R^n/L^n)^{1-\sigma}$, which represents the market-size effect; and $[\lambda^n R^n/L^n + \lambda^s R^s/L^s]^{-(1-\sigma)/\sigma}$, which captures the price effect.

The market-size effect relates the direction of technical change to the potential market for factor-specific innovations. For example, for given prices, a reduction in pollution (relative to a constant labour supply) reduces the potential profits from innovations in the pollution-intensive sector, and directs R&D expenditure to the labour-intensive sector. The price effect works in the opposite direction. Imagine, for example, a reduction in pollution at the world level for given domestic supply (because pollution is reduced elsewhere), this leads to higher prices for dirty goods. As a consequence, innovation in the pollution-intensive sector becomes more attractive.

As we discussed above, under autarchy a pollution reduction in the North always results in pollution-saving technological change. In the presence of international trade, this is no longer necessary. In this case, indeed, it is the world supply of factors rather than the northern one to determine the price level. Accordingly, changes in the northern pollution supply have a relatively weaker impact on prices than before. As northern pollution is reduced, innovation in the pollution-intensive sector becomes less attractive through the market-size effect and this tends to reduce N_R/N_L. Compared to autarchy, the mitigating effect of an increase in the relative price of the polluting goods is now less salient. Hence, more stringent environmental policy makes N_R/N_L decrease more under free trade than autarchy. Whether this implies a pollution-saving or pollution-using technical change relative to autarchy depends once more on whether polluting inputs and labour are gross substitutes or gross complements, see section 1.4.1.

Substituting (1.25) into (1.32) and using the new expression to substitute for the technology bias in (1.27), we find the condition that determines equilibrium pollution supply in the North:

$$\Omega^n \frac{\overline{E}}{L} - (\Omega^n + 1) \frac{R^n}{L^n} = \left(\frac{R^n}{L^n}\right)^{1-\sigma} \left[\frac{R^n}{L^n} + \lambda^s \frac{\Omega^s - \Omega^n}{\Omega^s + 1} \left(\frac{\overline{E}}{L} - \frac{R^n}{L^n}\right)\right] \tag{1.33}$$

This equation solves for pollution in the North under free trade and can be compared to the corresponding equation for autarchy, (1.30). Notice that, for given R^n/L^n, the right-hand side of (1.33) is larger than the one in (1.30), provided that $\Omega^s > \Omega^n$ (and smaller otherwise). Hence, when opening up to trade the North reduces (increases) pollution supply if it was relatively clean (dirty) in autarchy. Thus, the effect of trade on pollution in the North is similar to the undirected technology case. The reason is that the technology response to trade in the North is governed by the same incentives as the environmental policy response: to exploit the comparative advantage and benefit from the trade-induced increase in the relative price for labor-intensive goods, the North shifts production to the the labour-intensive sector not only by polluting less but also by innovating more in that sector.

In contrast, the effects of trade in the South might change due to fact that trade induces technical change and that this change is determined by conditions in the North.

In terms of figure 1.2, when opening up to trade, the right-hand side curve of the North (the dashed line) shifts up so that the intersection necessarily moves to the left for North. The equilibrium under trade in the North is indicated by the point F^n. Just as in the section 1.3 we know that prices and technology are common to the two regions. To determine the equilibrium for the South we just need to find the intersection of the LHS^s curve with the horizontal line through F^n. It is clear that this intersection might be above or below A^s, implying opposite effects of international trade on pollution in the South. The rest of this section is devoted to discussing this point.

Let's continue assuming $\Omega^s > \Omega^n$ for concreteness. This implies that the

North pollutes relatively less than the South in the autarchy equilibrium. When the South opens up to trade trade with the relatively cleaner North, the price of the pollution-intensive goods increases for any given level of pollution in the South, see (1.26). This is the conventional terms-of-trade effect that makes it attractive for the South to specialize in the production of the dirty good and hence to increase pollution.

The increase in p_R/p_L might be mitigated and even offset by a fall in the technology bias N_R/N_L, see (1.20). Indeed, when the North opens up to trade, N_R/N_L falls.[17] The North changes the direction of technical change towards the sector in which it has a comparative advantage. When this happens, the South faces pollution-using technical change if $\sigma < 1$, but pollution-saving technical change if $\sigma > 1$. From (1.27) we see that we need an increase in the technology bias $(N_R/N_L)^{(1-\sigma)/\sigma}$, that is pollution-saving technical change, to offset the terms of trade effect (i.e. the fact that the term in brackets falls when opening up to trade).

This means that, as long as the goods are gross complements, the induced technical change effect has the same direction as the terms-of-trade effect, while it has an opposite effect when $\sigma > 1$. In other words, if $\sigma < 1$, not only for the North but also for the South trade has the same effect as with undirected technological change. When goods are gross substitutes, instead, it is possible that the effects of international trade on pollution decisions in the South are reversed.

In Figure 1.3 we presents numerical examples to show that it is indeed possible that the South reduces pollution upon opening up to trade. The parameters values we used[18] were such that $\Omega^s > \Omega^n$, so that the South pollutes more than North. Above the line, combinations of the elasticity of substitution σ and the diffusion parameter δ are such that the South pollutes less in free trade than in autarchy; below the line, the opposite holds. As derived above, if $\sigma < 1$, trade always increases pollution in the South. The figure further reveals that better substitution or more diffusion of technologies make it more likely that trade improves the environment in the South. The reason is, first, that with a larger elasticity of substitution trade results is smaller price changes so that the conventional terms-of-trade effect that drives pollution

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[17] We know that when the North opens up to trade its pollution supply (R^n/L^n) falls. From (1.16) this implies that the northern relative price of pollution-intensive goods p_R/p_L will then rise. Finally, from (1.20), this implies that N_R/N_L falls.

[18] For the simulations, the following values of the parameters were used: $L^n = 1, L^s = 3, \bar{E}/L = 0.5, g = 0.015, \beta = 0.2, \rho = 0.025, \varsigma = 1, \phi = 0.06, \tau_m = 0$.

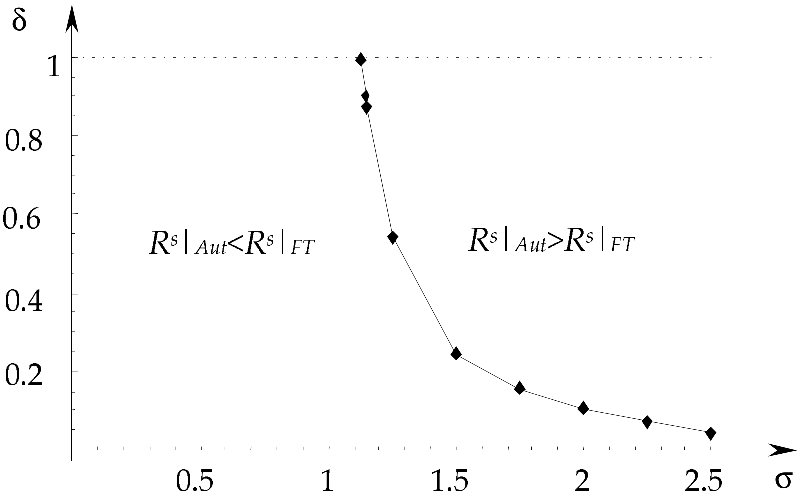

Figure 1.3: *Pollution policy in the South under Free Trade*

havens is small. Second, with more diffusion (larger δ), the effective size of the South, as measured by λ^s, is larger and any change in Northern pollution supply has a smaller effect on world prices and a relatively larger effect on the market size for innovations in the labour-intensive sector. Thus, more diffusion implies a large change in the technology bias. [19]

We end this section by discussing the case with $\Omega^n > \Omega^s$, in which the North pollutes more than the South, reversing our earlier assumption on comparative advantage. Indeed, now the North has a comparative advantage in the production of polluting goods and starts innovating more in the pollution-intensive sector, once trade is opened. As a result, N_R/N_L now rises. If $\sigma < 1$, this implies pollution-saving technical change and the South reduces pollution after trade is opened. This result is qualitatively similar to the one obtained with terms-of-trade effects only in section 4. If $\sigma > 1$, however, trade induces pollution-using technical change, so that the technology effect might offset the terms-of-trade effect. For sufficiently large σ and δ, the South will increase pollution. Hence, if the innovating region has a comparative advantage in pollution-intensive goods, if these goods are good substitutes for other goods and if a large fraction of the new technologies diffuse to the imitating

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[19] In figure 1.2, a larger σ makes the RHS curves flatter, while a larger δ, by increasing λ^s, shifts the RHS^n, FT curve up. As a result, the vertical distance between the autarchy points A^n and A^s is small and the vertical distance between A^n on the one hand, and F^n and F^s on the other hand, is large, such that it becomes more likely that F^s is above A^s.

region, trade is bad for the environment in both regions.

1.5 Summary and conclusions

In our model the North innovates and technologies diffuse to the South. Since only a fraction of the technologies diffuse, the South is less productive and has lower income than the North. By construction, this income difference does not lead to differences in environmental stringency in our model. Instead, a country that consumes a relatively large part out of income has a relatively large demand for environmental quality, as produced consumption goods and environmental amenities are traded off in utility. Whether the South or the North has higher demand for environmental quality, thus depends on investment opportunities and investment distortions. On the one hand, the North has to incur the cost of innovation (while the South gets innovations for free), which makes consumption scarce and reduces demand for environmental quality in the North. On the other hand, intermediates are priced above cost in the North. This introduces a distortion not present in the South and reduces investment. Which of the two effects will prevail will depend on the level of subsidies to technological change.

In this chapter we have discussed the two possibilities separately, one in which the North pollutes less than the South, and the other in which it pollutes more. These situations correspond to a comparative advantage for pollution-intensive goods in the South or in the North, respectively. When trade is opened, prices change and the regions exploit their comparative advantage. By this terms-of-trade effect, environmental quality always improves in the country that has most stringent environmental policy in autarchy and always deteriorates in the other. Induced technological change never reverses this pattern in the North, but may do so in the South provided that pollution-intensive and labour-intensive goods are gross substitutes ($\sigma > 1$).

While the terms-of-trade effect has opposite effects on environmental quality in the two regions, the induced technology effect affects environmental quality in both regions in the same direction. The reason is that technology is determined by profit conditions in the North and then diffuses to the South. Northern innovation activities will shift in the direction of the sector that uses intensively the relatively abundant factor (pollution or labour) and thus increases the relative supply from this sector. If these goods are gross substitutes for goods from the other sector, world demand shifts away from goods in which the South has a comparative advantage. Hence, if the South has a comparative advantage in pollution-intensive goods, the induced technology effect nevertheless makes production of these goods less profitable and tightening environmental policy become less costly in the South. Thus, effectively, abatement costs have fallen, the net effect may be that trade induces more stringent environmental in both regions. However, if the North started as the dirty region, the net effect may be that trade induces more pollution in both regions by raising abatement costs.

Technology diffusion from North to South is therefore not ambiguously good for the environment in the South, since whether technologies are pollution-using or pollution-saving depends on the profitability of different innovation projects, which in turn depends on comparative advantages and substitutability between goods with different pollution-intensity. Our results highlight that endogenous technological change is potentially but not necessarily a blessing. The main reason is that the lack of intellectual property rights protection in the South creates distortions. Innovating firms cannot recoup their costs in the South and only direct their efforts to Northern markets, so that the resulting technologies cannot be in the interests of the South in all respects. Moreover, innovation costs are asymmetrically born by Northern consumers, which creates asymmetries in the costs associated to environmental policies, the driving force behind pollution havens.

APPENDIX

A

THE C/Y RATIO IN THE TWO REGIONS

Consider the final good market equilibrium condition (1.2). In both the North and the South, the total cost of producing machines in sector i amounts to $v\, m_i\, N_i$ $(i = R, L)$, where v represents the unit cost of production and $m_i\, N_i$ is the total amount of machines produced. Since the machines share in intermediate producers' output is given by $1-\beta$, we rewrite total cost as $(v/p_{m_i})\,(1-\beta)\, p_i\, Y_i$. Substituting the appropriate expressions for prices and marginal costs in the two regions, $p_m^n = (1-\tau_m)$ and $p_m^s = v = 1-\beta$, and summing over the two sectors, we find total expenditure in machines in the North and in the South, respectively, as:

$$M^n = (1-\beta)\left(\frac{1-\beta}{1-\tau_m}\right) Y^n, \text{ and } M^s = (1-\beta)Y^s.$$

In the South, whatever is not needed for physical investment will be consumed. The C/Y ratio in the South will then be given by:

$$\left(\frac{C}{Y}\right)^s = 1-(1-\beta) = \beta.$$

In the North, however, investment also occurs in R&D. To characterize the consumption-output ratio in the North, we need to derive the equilibrium R&D investment outlays. Starting with the directed technical change case, from (1.6) it is possible to write the R&D investment in each sector as $D_i = gN_i(N_R + N_R)^{\psi}/\eta$, where g is the growth rate of the economy. From (2.18), (1.10), and the definition of the interest rate along the balanced growth path $\left(r = \eta(N_R + N_R)^{-\psi}\,\pi_i\right)$, we find $N_i/(\eta(N_R+N_R)^{-\psi}) = p_i Y_i \beta(1-\beta)/r$. Summing over both sectors, we can write the total expenditure in research and development, $D = D_L + D_R$, as

$$D = (1-\beta)\beta\frac{g}{r}Y.$$

Following the same steps it is straightforward to obtain the same expression for the case of undirected technical change.

Accordingly, we can write the consumption to output ratio in the North as follows:

$$\left(\frac{C}{Y}\right)^n = 1 - (1-\beta)\left(\frac{1-\beta}{1-\tau_m}\right) - (1-\beta)\beta\frac{g}{r}.$$

CHAPTER
TWO

CARBON LEAKAGE REVISITED[1]

An important threat to climate policy is that actions undertaken without universal participation may prove to be ineffective: any partial agreement to reduce emissions, of carbon dioxide (CO_2) for example, may be undermined by the behaviour of countries outside the agreement. Indeed, increases in CO_2 emissions by unconstrained countries can off-set the reductions secured by the agreement participants, a phenomenon known as *carbon leakage*.[2]

The behaviour of unconstrained countries in reaction to a reduction of CO_2 emissions of other countries is mainly driven by two economic mechanisms. First, when the production of energy-intensive goods is reduced in constrained countries due to the introduction of an emission constraint, the international prices of such goods will increase. This gives countries outside the abating coalition incentives to expand their production of these goods and export them to signatory countries (the *terms-of-trade* effect). Clearly, this implies an increase in emissions by countries outside the agreement. The second mechanism of carbon leakage works through the price of fossil fuels: as the price of fossil fuels decreases following the reduction in demand on the part of

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[1] This chapter is a slightly revised version of Di Maria and van der Werf (2005).

[2] Estimates of the size of this effect rely on Computable General Equilibrium (CGE) models. The leakage rates for the Kyoto Protocol (the percentage of the reduction in emissions offset by the increase in emissions by countries outside the Protocol) reported in the literature range from 2% to 41% (see, for example, Burniaux and Oliveira-Martins 2000, Light, Kolstad, and Rutherford 2000). Babiker (2005) even finds a leakage rate of 130% for one of his scenarios. These differences in the estimates stem from widely differing assumptions with respect to the degree of international market integration, substitution and supply elasticities, and market structure.

the constrained countries, countries outside the agreement might decide to substitute other inputs with fossil fuels, thus increasing their emissions (the *energy-market* effect).

In sum, climate change policy affects the relative prices of both goods and factors, thus inducing the leakage of carbon emissions. These price changes, however, also modify the incentives for innovation, changing the level and, most importantly, the direction of technological change (i.e. how technology levels develop across industries). This effect, known as induced technological change, was already postulated by Hicks (1932), and has since been the focus of many influential contributions, both theoretical and empirical.[3] Once the available technology changes as a result of climate policy, however, so do the responses of the unconstrained countries. Yet, this additional mechanism has to date been almost completely ignored in the climate change policy literature.[4]

In this chapter, we study the consequences of induced (directed) technological change on carbon leakage using a stylized theoretical model of the interactions between constrained and unconstrained countries, which focuses on transmission mechanisms based on terms-of-trade effects. In order to be able to highlight the effects of induced technological change, we model two countries that are perfectly symmetric as refers to preferences, technology and endowments. In this way we rule out any other potential source of carbon leakage, which would cloud the effects of technological change. Indeed, we only allow the two countries to differ in one crucial respect: one country imposes a binding emission cap, while the other remains unconstrained. As the countries are symmetric before the imposition of the cap, the adjustment pro-

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[3] For early contributions, see Kennedy (1964) and Drandakis and Phelps (1965). Recently, Acemoglu (1998, 2002a) has provided a tractable theoretical framework to investigate the issue. Among the empirical contributions, Newell, Jaffe, and Stavins (1999) study the effect of energy prices and government regulations on energy-efficiency innovation. They show that changes in energy prices affect the direction of innovation for some products, and induce changes in the subset of models offered for sale. They conclude that "the endogeneity of the direction, or composition of technological change is surely at least as significant [as] the overall pace of technological change" (p. 971). Popp (2002) shows that changes in energy prices (including the effects of environmental policy) positively and quickly affect environmentally friendly innovations.

[4] Grubb, Chapuis, and Ha Duong (1995) first noted the importance of induced technological change for carbon leakage. However, in their paper induced technological change does not come from profit-maximizing behaviour. Instead, it is assumed to occur through an exogenous decrease in the emissions intensity of non-abating countries, following the decrease in emissions intensity in abating countries.

cess represents a pure response to policy. In this sense, the chapter analyzes a 'policy-induced pollution-haven effect'.

To single out the contribution of technological change in the adjustment process, our analysis proceeds in two steps. We start from a situation of complete symmetry and analyze the effect of introducing an exogenous emission cap. The first step refers to analyzing a model where unilateral climate policy induces trade (in either energy-intensive goods, or directly in energy), but (the composition of) technology does not change. This is what we call the 'undirected technical change' scenario, where purely trade effects are at work. We then compare this benchmark to the case where technology levels of the labour- and energy-intensive industries are allowed to develop at different rates, i.e. the 'directed technical change' scenario. We show that, when (the composition of) technology is allowed to adjust endogenously, induced technological change always leads to a reduction in the degree of carbon leakage. We refer to this as the *induced-technology* effect.

Our work contributes to the theoretical literature on carbon leakage by highlighting the role of directed technical change in this framework. The early literature on the topic addressed asymmetric international environmental policy from a public economics point of view (e.g. Hoel 1991, Barrett 1994, Carraro and Siniscalco 1998). Stressing the roles of free-riding incentives and strategic behaviour among nations, but abstracting from both technical change and international trade, this literature concludes that emissions among countries are strategic substitutes and that unilateral climate policy will lead to leakage of emissions. More recently, however, Copeland and Taylor (2005) show that in the presence of international trade and environmental preferences, a country's response to a rest-of-world emissions reduction is ambiguous: emissions among countries can be either strategic complements or substitutes depending on key elasticities in the model. In their static two-good, two-factor, K-country model without technical change, this result follows from allowing for income and substitution effects on the consumption side to offset the terms-of-trade effect on the production side. The mechanism underlying their result therefore differs from ours, both in terms of modelling and in terms of economic content.

Closer in spirit to our work, Golombek and Hoel (2004) study the effect of international spillovers of abatement technology on leakage, using a static partial equilibrium two-country, one-good model with transboundary pollution. In each country a central planner chooses research and development (R&D) expenditures and abatement levels to minimize total costs that include environmental damages. Research activities lead, by assumption, to reductions in abatement costs, while international technology spill-overs allow technology to diffuse across borders at no cost. Hence, the authors effectively build in their model a mechanism that counteracts the free-riding incentives underlined by previous literature. In our model, on the other hand, the nature of technical change is endogenous, as it is itself driven by profit incentives, and depends on the characteristics of production.

The rest of the chapter develops as follows. We introduce the model in section 2.1. In section 2.2 we present equilibrium conditions for the four versions of our model: with and without unilateral climate policy, and with and without directed technical change. Section 2.3 contains the main results. We first introduce the terms-of-trade effect and study carbon leakage when entrepreneurs cannot aim new technologies to one of the sectors; we then focus on carbon leakage under directed technical change and show how the induced technology effect changes the results found before. We finally provide some conclusions in section 2.4.

2.1 The Model

Our economy consists of two countries, c and u, that have identical production technologies and endowments, while only differing in their environmental policies.[5] We assume that country c (for *constrained*) imposes a binding cap on polluting emissions. We focus on a situation of free trade noting that, as long as the two countries do not differ in environmental policies, there will be no actual scope for trade.

In each country, final output Y is obtained as a CES aggregate of two (intermediate) goods, Y_E and Y_L, with an elasticity of substitution equal to ε:

$$Y^r = \left[(Y_E^r)^{\frac{\varepsilon-1}{\varepsilon}} + (Y_L^r)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}}, \tag{2.1}$$

where $r = c, u$ is the country index.[6] We assume that good Y_E is produced using energy (E) and a specialized set of differentiated machines. The range of

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[5] In this chapter we are only interested in the effect of climate policy on technology and in the ensuing production choices. We therefore do not discuss growth rates or welfare. Since in addition we assume balanced trade, (intertemporal) preferences play no role and the consumption side of the model is redundant.

[6] For simplicity, we set the share parameters in the CES to one, as they will only introduce an additional constant term in the expressions.

types of machines available to produce energy intensive goods is indicated by N_E. Instead, Y_L is produced using labour (L_L) and a different set of machines, whose range is indicated by N_L. Following Acemoglu (2002a), the production functions for the intermediate goods are as follows:

$$Y_E^r = \frac{1}{1-\beta}\left(\int_0^{N_E} k_E^r(i)^{(1-\beta)} di\right)(E^r)^\beta, \tag{2.2}$$

and

$$Y_L^r = \frac{1}{1-\beta}\left(\int_0^{N_L} k_L^r(i)^{(1-\beta)} di\right)(L_L^r)^\beta, \tag{2.3}$$

where $\beta \in (0,1)$ and $k_j^r(i)$ is the amount of machines of type i employed in sector $j = L, E$ in country r. Both intermediate goods are traded internationally.

To produce each type of machines, producers need a blueprint invented by the R&D sector, as will be discussed below. We assume that machines developed to complement one factor of production cannot be usefully employed in the other sector and that blueprints can be traded internationally. Accordingly, N_E and N_L represent global levels of technology and producers in each country can use all machine types globally available for their sector. For a given state of technology, that is for given N_E and N_L, both (2.2) and (2.3) exhibit constant returns to scale. However, when N_E and N_L grow due to R&D activities the returns will be increasing at the aggregate level.[7]

We assume that in each country an amount of labour equal to $\overline{L}$ is inelastically supplied at each point in time and that it is immobile across countries. Labour can either be employed in the production of the labour intensive good Y_L or in the production of energy:

$$\overline{L} = L_L^r + L_E^r, \tag{2.4}$$

where L_E^r is the amount of labour in energy production in country r. As in Babiker (2005), we assume that energy has to be produced using labour and some fixed factor. Consequently there are decreasing returns to labour in energy production:

$$E^r = (L_E^r)^\phi, \tag{2.5}$$

where $\phi \in (0,1)$. Energy generation causes emissions of carbondioxide. We assume that CO_2 emissions, Z, are proportional to the amount of energy produced, so that $Z = E$.

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[7] In other words, our model exhibits endogenous growth through variety expansion. See for example Grossman and Helpman (1991).

When country c introduces a binding constraint on the amount of carbon-dioxide emitted, it *de facto* imposes a cap on the amount of labour allocated to energy production. Indeed, when Z^c is the maximum amount of emissions permitted at any point in time, the allocation of labour in country c must satisfy $L_E^c = (Z^c)^{1/\phi}$.

The last part of our model consists of the process of technical change. We consider two alternative possibilities in this chapter: technical change can either be 'undirected' or 'directed'. With *undirected* or 'traditional' technical change, prospective innovators invest in the development of blueprints whenever it is profitable to do so, yet they cannot choose the sector they want to develop a new machine for. Instead, we assume that the newly developed blueprint will be energy-complementing with probability $\gamma \in (0, 1)$ and it will be labour-complementing with probability $(1 - \gamma)$. As a consequence the (expected) relative marginal productivity is constant, as is common in traditional (one-sector) models of endogenous growth.[8]

Using a lab-equipment specification for the process of technical change, we assume that investing one unit of the final good in R&D generates ν new innovations.[9] The total number of innovations in this case will therefore develop according to:

$$\dot{N} = \nu \left(R^c + R^u \right), \tag{2.6}$$

where R^r indicates total R&D investment by country r, and a dot on a variable represents its time derivative, i.e. $\dot{x} = \mathrm{d}x/\mathrm{d}t$.

The second regime of technical change that we consider is *directed* technical change.[10] In this case prospective innovators, besides deciding upon the amount of their R&D outlays, are able to choose the sector they want to target their innovation efforts to. Hence they will invent new machines for the sector that promises the highest returns. The development of new types of machines

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[8] Hence, with undirected technical change the relative level of technology in the two sectors, N_E/N_L, is exogenous and constant. Moreover, since N_E/N_L equals $\gamma/(1-\gamma)$, any value of N_E/N_L can be calibrated by an appropriate choice of the probability γ.

[9] See Rivera-Batiz and Romer (1991).

[10] The seminal work in this field is due to Daron Acemoglu. See, for example, Acemoglu (2002a).

takes place according to the following production functions:[11]

$$\begin{aligned} \dot{N}_E &= \nu\,(R_E^c + R_E^u)\,, & (2.7)\\ \dot{N}_L &= \nu\,(R_L^c + R_L^u)\,. & (2.8) \end{aligned}$$

A new blueprint must be developed before the innovator can sell it to producers, thus the costs of R&D are sunk. As a consequence, machine producers must wield some monopoly power in the market for machines, in order to recoup the development costs. For this we assume that an innovator is awarded a global patent for her invention and that patents are perfectly enforced in both countries. As a result, each innovation will take place only once and no international overlap in blueprints occurs.[12]

Furthermore, we simplify the analysis by assuming that machine production is local, that is innovators license their blueprints to one producer in each region, so that blueprints are traded across countries, but machines are not.

2.2 The Equilibrium

In this section we derive the general equilibrium allocation of labour. We first derive a necessary condition for equilibrium on the goods and factor markets. For the model with undirected technical change, this condition gives the general equilibrium amount of labour in energy production. For the model with directed technical change we need to take another step and also study the equilibrium on the market for innovations. Joint consideration of these two conditions will give the general equilibrium allocation under directed technical change.

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[11] For simplicity we assume that R&D is equally productive in the two sectors. Relaxing this assumption introduces a constant in the expressions that follow, but does not alter our qualitative results.

[12] Di Maria and Smulders (2004) also deal with directed technical change in an open-economy framework, but develop a North-South model to explain pollution-haven effects. They focus on the asymmetry of intellectual property rights' protection: since patents are not protected in the South all innovation takes place in the North. As a consequence the relevant market for innovators is the northern one, and the technology developed is inadequate to the factor composition in the South. Hence, the level of emissions in the South might increase once international trade in goods is allowed.

2.2.1 Equilibrium on the goods and factor markets

The market for the final good is perfectly competitive and we choose the final good's price as the numeraire. It follows that a necessary condition for the optimal demand for labour- and energy-intensive goods is that the marginal product of each intermediate good equals its price. From (2.1) we get, in relative terms:

$$\frac{Y_E^{dr}}{Y_L^{dr}} = \left(\frac{p_E}{p_L}\right)^{-\varepsilon}, \tag{2.9}$$

where p_j is the price of good Y_j, $j = E, L$. Notice that we introduced a superscript d to indicate demand and avoid confusion with supply in (2.2) and (2.3). Prices will be equalized across the two regions since countries are either symmetric or trade at no cost.

Producers of the intermediate good Y_j maximize profits taking prices and technology as given. In particular, they choose the amount of inputs taking as given the prices of their output (p_j), of the primary input they use (w_j) and of the machines they use ($p_{k_j(i)}$ for a machine of type i complementing factor j), and the range of available machines N_j.[13]

Using (2.2) and (2.3) we can derive the local demand for a machine of type i in each sector from the first-order conditions with respect to each type of machine $k_j(i)$:

$$k_E^r(i) = \left(\frac{p_E}{p_{k_E(i)}}\right)^{1/\beta} E^r \quad \text{and} \quad k_L^r(i) = \left(\frac{p_L}{p_{k_L(i)}}\right)^{1/\beta} L_L^r. \tag{2.10}$$

By the same token we can derive the (inverse) local demand for energy and labour from the first-order conditions with respect to primary inputs:

$$w_E = \frac{\beta}{1-\beta} p_E \left(\int_0^{N_E} k_E^r(i)^{(1-\beta)} di\right) (E^r)^{\beta-1}, \tag{2.11}$$

$$w_L = \frac{\beta}{1-\beta} p_L \left(\int_0^{N_L} k_L^r(i)^{(1-\beta)} di\right) (L_L^r)^{\beta-1}. \tag{2.12}$$

As mentioned before, the holder of a patent licenses production to only one producer in each region. Consequently, local producers act as monopolists on their local market. We assume that the production of machines in both sectors entails a constant marginal cost equal to ω units of the final good, and that machines depreciate immediately after use. Each monopolist maximizes her

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[13] Throughout the chapter we will refer to energy (E) and labour used in the production of Y_L (L_L) as primary inputs, although in the model labour is the only "truly" primary input.

profits subject to the appropriate demand function in (2.10). As a result, each monopolistic producer will set her price as a constant mark-up over marginal cost, that is $p_{k_j(i)} = \omega/(1-\beta)$. Letting $\omega = 1-\beta$ for convenience, we can set the price of machines in both sectors equal to 1.[14]

Using this result we obtain an expression for the relative supply of goods that depends on relative prices, relative (primary) factors supplies and relative technology,

$$Y^w = p^{(1-\beta)/\beta} S^w N. \tag{2.13}$$

In the remainder of the chapter we define variables without a subscript as ratios, with the convention that the variables at the numerator refer to the energy sector E, while the ones at the denominator refer to the clean sector. Hence, we refer to $N \equiv N_E/N_L$ as the (global) technology ratio. Moreover, we let the global relative factor supply be $S^w \equiv (E^c + E^u)\ /\ (L_L^c + L_L^u)$, and define as $Y^w \equiv (Y_E^c + Y_E^u)\ /\ (Y_L^c + Y_L^u)$ the world relative supply of intermediate goods. Superscript w indicates that the variable concerned represents a global (world) amount or ratio.

Equating relative supply (2.13) and relative demand (2.9) yields the market clearing relative price for intermediate goods, for given technology:

$$p = (NS^w)^{-\beta/\sigma}, \tag{2.14}$$

where we define $\sigma \equiv 1 + (\varepsilon - 1)\beta$. From (2.14) we see that a higher level of technology in the sector for energy intensive goods, or a higher relative supply of energy decreases the relative price of the dirty good.

We now turn to the market for factors. Substituting machine demands (2.10) into the inverse demand functions for energy (2.11) and labour (2.12), we obtain an expression for the relative factor rewards. Using this and the market clearing relative price for intermediate goods (2.14), we get the following expression for the relative factor rewards for given technology:

$$w = N^{(\sigma-1)/\sigma} (S^w)^{-1/\sigma}. \tag{2.15}$$

The relative price of energy decreases with energy supply, while the effect of the technology ratio N depends on whether σ is larger or smaller than unity. Solving equation (2.15) for S^w gives $S^w = N^{\sigma-1} w^{-\sigma}$, which informs us that σ

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[14] Notice that all machines are equally productive in intermediate goods production and entail the same cost. Thus, the amount of each machine used in sectorial production will be the same, k_j say. This symmetry simplifies the structure of the sectorial production functions as we may write: $\int_0^{N_j} k_j(i)^{(1-\beta)} di = N_j k_j^{(1-\beta)}$, for $j = E, L$.

is the elasticity of relative factor demand with respect to their relative price. As will be discussed later, the effect of the technology ratio on relative factor rewards depends on whether relative energy demand is elastic or inelastic.[15]

To fully characterize the equilibrium on the goods and factor markets for given technology, we need to determine the way in which labour is allocated between production of the labour intensive intermediate good and energy production. As noted in section 2.1, when country c faces a binding emission constraint, the amount of labour in energy production is exogenously determined by the cap, $L_E^c = (Z^c)^{1/\phi}$. In an unconstrained country however, each energy producer chooses the amount of labour so as to maximize her profits, subject to the production function in (2.5) and taking prices w_L and w_E as given. This gives an unconstrained country's demand for labour in energy production as a function of relative factor prices:

$$w = \frac{1}{\phi \left(L_E^r\right)^{\phi-1}}.$$

Equating this expression and (2.15) we find an expression representing the equilibrium allocation of labour in country u, for a given technology ratio N and for given energy production in the other country:

$$\phi^{-\sigma} N^{1-\sigma} \left[(L_E^c)^{\phi} \left(L_E^u\right)^{\sigma(1-\phi)} + \left(L_E^u\right)^{\phi(1-\sigma)+\sigma} \right] + L_E^c + L_E^u = 2\overline{L}. \qquad (2.16)$$

In this expression we allow for the possibility that each country chooses a different level of labour in energy production. It is clear that, as long as no binding emission cap is introduced, a symmetric expression holds for country c. In this case, given that countries are identical, they will choose the same equilibrium amount of labour in energy production so that we can rewrite the above expression, letting $L_E^u = L_E^c = L_E$, as

$$\phi^{-\sigma} N^{1-\sigma} L_E^{\phi(1-\sigma)+\sigma} + L_E = \overline{L}. \qquad (2.17)$$

Here L_E is the amount of labour employed in energy production in each country, when both countries are unconstrained.

In sum, when country c faces a binding emission constraint, its emissions, energy generation and amount of labour in energy producion are determined by the cap. Yet expression (2.16) still holds for the unconstrained country, u,

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[15] From the definition of σ as $1 + (\varepsilon - 1)\beta$, it is clear that $\sigma \gtrless 1 \Leftrightarrow \varepsilon \gtrless 1$. Thus relative factor demand is elastic if and only if intermediate goods are gross substitutes in the production of the final good, and inelastic if and only if they are gross complements.

and solves (implicitly) for the amount of labour in energy production in the unconstrained region for given N.

As we saw in section 2.1 the technology ratio N is constant when technical change is undirected. Consequently, in this case equations (2.16) and (2.17) determine the general equilibrium allocation of labour. However, for the case of directed technical change we need to study the equilibrium on the market for innovations to determine the general equilibrium allocation of labour.

2.2.2 Equilibrium on the market for innovations

Under directed technical change innovators choose both the amount and the direction of their innovation efforts. Quite naturally they will invest in the sector which is expected to yield the highest rate of return. Using (2.10), the instantaneous profits are given by the following expressions:

$$\pi_E = \beta p_E^{1/\beta} E^w \quad \text{and} \quad \pi_L = \beta p_L^{1/\beta} L_L^w. \tag{2.18}$$

At each point in time, then, the direction of innovation will be determined by relative profits: $\pi = p^{1/\beta} S^w$. This expression clearly shows that the entrepreneurs' choice of the sector to invest in is determined by the relative price of the intermediate goods (the *price effect*) and by the relative amount of factors to which a machine type is complementary (the *market-size effect*). In particular, for given technology, a decrease in energy supply leads to a reduction in relative profits through the market size effect and to an increase through the price effect, see (2.14). Which of the two effects prevails depends on the elasticity σ, as will be discussed later.

Each potential innovator maximizes the net present value of the stream of future profits that she expects to enjoy over time. Along the balanced growth path of the economy, profits will not change over time.[16] Since entry is free in the R&D sector, we know that the value of an innovation cannot exceed its cost (see (2.7) and (2.8)). Moreover, along the balanced growth path both types of innovation must occur at the same time, leading to the following no-arbitrage equation for the research sector:

$$\pi_E \nu = \pi_L \nu.$$

Substituting the appropriate expression for profits from (2.18), this can be re-

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[16] We define a balanced growth path as a situation in which prices are constant and N_E and N_L grow at the same constant rate.

arranged to read,

$$p^{1/\beta} S^w = 1. \tag{2.19}$$

This no-arbitrage equation enables us to solve for the equilibrium level of the technology ratio N. Indeed, using the expression for relative prices in (2.14), we may solve (2.19) for N, obtaining the following expression for the balanced growth path equilibrium ratio of technology levels in the two sectors:

$$N = (S^w)^{\sigma-1}. \tag{2.20}$$

From this expression we see that, as noted above, the effect of a decrease in energy supply on the direction of technical change, that is on whether N increases or decreases, depends on the size of σ. When labour- and energy-intensive goods are gross complements in final goods production ($\sigma < 1$), the price effect in (2.18) outweighs the market size effect and a decrease in energy supply induces an increase in the range of energy complementary machines. However, when $\sigma > 1$ the result is reversed and the reduction in energy supply induces an increase in the range of labour-complementary machines.

2.2.3 General equilibrium under directed technical change

In the previous sections we have derived equilibrium conditions for the goods and factor markets and for the market for innovations. We are now ready to derive the general equilibrium allocation of labour for the model with directed technical change, as it obtains when both markets are in equilibrium at the same time.[17]

Substituting (2.20) into (2.16) yields the general expression for the equilibrium under directed technical change:

$$\phi^{1/(\sigma-2)} \left[(L_E^c)^{\phi} \, (L_E^u)^{(\phi-1)/(\sigma-2)} + (L_E^u)^{(\phi(\sigma-1)-1)/(\sigma-2)} \right] + L_E^c + L_E^u = 2\bar{L}. \tag{2.21}$$

Interpreting L_E^c as the constrained level of labour used in energy generation in country c following the introduction of an emissions cap, this expression solves for L_E^u in the unconstrained country under directed technical change.

Alternatively, assuming that no environmental policy is in place, we can interpret (2.21) as one of the two (symmetric) expressions that determine the

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[17] It is possible to show that the model has an interior stable equilibrium for $\sigma \in (0, (1+\phi)/\phi)$. The stability of the equilibrium requires that in the (L_E, N) plane the line depicting the goods market equilibrium (2.16) is steeper than the no-arbitrage equation (2.20), at the point of intersection. See the Appendix to this chapter for the details.

equilibrium level of $L_E^c = L_E^u = L_E$ under directed technical change. Substituting L_E for the country specific variables yields the following expression:

$$\phi^{1/(\sigma-2)} L_E^{(\phi(\sigma-1)-1)/(\sigma-2)} + L_E = \overline{L}. \qquad (2.22)$$

The above equations summarize the long-run equilibrium of our model with and without unilateral climate policy, under directed technical change. Indeed, they solve implicitly for the optimal level of L_E^u (L_E, respectively), from which we can immediately derive all the other variables of the model.

2.3 Unilateral climate policy and carbon leakage

We now turn to the analysis of the effects of unilateral climate policy, in terms of carbon leakage, across different regimes of technical change. To compare different scenarios, we need to start from a common baseline. The natural baseline to choose is the long-run equilibrium of the model with directed technical change when both countries are unconstrained, equation (2.17). This baseline is characterized by the (symmetric) equilibrium level of labour devoted to energy generation L_E and by the corresponding (endogenous) technology ratio N. In order to have comparable baselines across technology regimes, we need to choose γ, the probability for an innovator to end up with an energy-complementing blueprint, such that $\gamma/(1-\gamma) = N$ equals the level prevailing under directed technical change, see Section 2.1.

Starting from this common equilibrium, we introduce an emissions constraint in one of the countries and study the degree of carbon leakage that occurs along the balanced growth path. We first study carbon leakage when technical change is undirected. Then we move on to the model with directed technical change and discuss how and why the results from this model differ from the model with 'traditional' endogenous growth.

2.3.1 Carbon Leakage under undirected technical change

Carbon leakage occurs when the unconstrained region increases its emissions in reaction to a reduction in emissions by the other country (i.e. when $L_E^u > L_E$). Intuitively it would seem clear that there should always be some carbon leakage: when a country exogenously reduces its supply of energy by introducing a limit to the amount of emissions, the energy intensive good becomes scarcer on its domestic market, giving rise to an increase in its relative price.

This creates some scope for trade: the unconstrained economy now enjoys a comparative advantage in the production of the dirty good and will expand its production thereof. As a consequence L_E^u and hence emissions Z^u increase. We call this the *terms-of-trade effect* of a unilateral emission constraint. This result indeed holds in the case of undirected technical change, as formalized by the following proposition.

Proposition 2.1. *When technical change is undirected, carbon leakage will always be positive along the balanced growth path.*

Proof. Take the ratio of (2.17) and (2.16) and rearrange to find:

$$\left(\frac{L_E^{\phi}}{(L_E^u)^{\phi}+(L_E^c)^{\phi}}\right)^{-1/\sigma}\left(\frac{2\overline{L}-L_E^c-L_E^u}{\overline{L}-L_E}\right)^{-1/\sigma}=\left(\frac{L_E}{L_E^u}\right)^{1-\phi}.$$

Assume that $L_E^u \leq L_E$. Then the right hand side is larger than or equal to one while the left hand side is smaller than one. So we have a contradiction, hence $L_E^u > L_E$. □

We illustrate this result in Figure 2.1, where the dark dashed line represents emissions (or equivalently energy production) in each country when both are unconstrained. The amount of emissions by the unconstrained country when the other country faces a binding emission constraint, under undirected technical change is represented by the solid black line.[18] The figure clearly shows that emissions in the unconstrained region always increase following the introduction of the cap. In addition, we see that the amount of energy produced in the unconstrained region is declining with σ, the elasticity of relative demand for energy with respect to its relative price. The higher this elasticity, the lower the demand for energy in the constrained economy following the imposition of the constraint, hence the lower the export-led increase in energy generation.

When technical change is endogenous but undirected, unilateral climate policy is undermined by emission increases by unconstrained countries. However, it seems intuitively clear that changes in relative prices *cœteris paribus*

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[18] The figures in this chapter are obtained from numerical simulations, using as baseline parameters values: $\overline{L}=1$, $\phi=0.4$, and $\sigma\in(0,3.5)$. For each value of σ the corresponding value for N for the model with directed technical change were computed and the appropriate γ calibrated such that both models start from the same baseline. We conducted numerous robustness checks for the local results derived in Propositions 2.2 and 2.4. In all cases the qualitative results were unchanged. For the sake of graphical clarity, the graphs are plotted over a smaller range for σ.

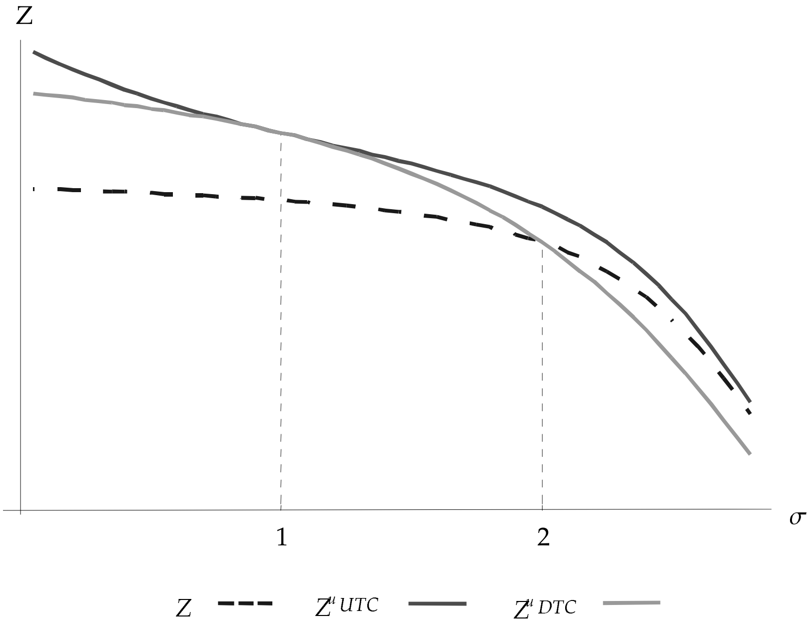

Figure 2.1: *Emissions in the unconstrained model (Z), in the constrained model under undirected technical change ($Z^u UTC$), and under directed technical change ($Z^u DTC$)*

will not lead to an increase in global emissions. Climate policy will shift production to the unconstrained country (proposition 2.1), but the increase in the relative price of the carbon intensive good will at the same time lead to a reduction in global energy demand. To address this formally, we look at the impact of a change in the level of the cap on total emissions, $\left[(L_E^c)^\phi + (L_E^u)^\phi\right]$, and derive the following result:

Proposition 2.2. *When technical change is undirected, global emissions will always decrease following a tightening of the emission constraint.*

Proof. By total differentiation of (2.16), we get:

$$\frac{\mathrm{d}L_E^u}{\mathrm{d}L_E^c} = -\frac{A(L_E^u)^{\sigma(1-\phi)}\phi(L_E^c)^{\phi-1}+1}{A(L_E^u)^{\sigma(1-\phi)}\left\{\phi(L_E^u)^{\phi-1}+\sigma(1-\phi)\left[(L_E^c)^\phi+(L_E^u)^\phi\right](L_E^u)^{-1}\right\}+1}\,. \tag{2.23}$$

Let $E^w \equiv \left[(L_E^c)^\phi + (L_E^u)^\phi\right]$ be total emissions. Thus, E^w decreases with a tightening of the cap whenever $\mathrm{d}E^w/\mathrm{d}L_E^c > 0$. Differentiating E^w, and rearranging terms shows that $\mathrm{d}E^w/\mathrm{d}L_E^c > 0$ requires:

$$\frac{\mathrm{d}L_E^u}{\mathrm{d}L_E^c} > -\frac{(L_E^c)^{\phi-1}}{(L_E^u)^{\phi-1}}\,.$$

This and (2.23) in turn imply that total emissions decline whenever

$$\frac{A(L_E^u)^{\sigma(1-\phi)}\phi(L_E^c)^{\phi-1}+1}{A(L_E^u)^{\sigma(1-\phi)}\left\{\phi(L_E^u)^{\phi-1}+\sigma(1-\phi)\left[(L_E^c)^{\phi}+(L_E^u)^{\phi}\right](L_E^u)^{-1}\right\}+1} < \frac{(L_E^c)^{\phi-1}}{(L_E^u)^{\phi-1}}.$$

Straightforward calculations show this to be equivalent to:

$$-A(L_E^u)^{\sigma(1-\phi)}\left[(L_E^c)^{\phi}+(L_E^u)^{\phi}\right](L_E^u)^{-1}-(L_E^c)^{\phi-1}+(L_E^u)^{\phi-1}<0.$$

Since $L_E^c < L_E^u$ and $\phi \in (0,1)$, the above inequality is always true. □

To illustrate this result, in Figure 2.2 we present the leakage rate, the ratio of the induced increase in emissions in the unconstrained country and the emission reduction in the constrained region, $\left[(L_E^u)^{\phi}-(L_E)^{\phi}\right]\Big/\left[(L_E)^{\phi}-(L_E^c)^{\phi}\right]$, as a function of σ. The leakage rate for the case of undirected technical change is represented by the dark line. As the figure shows, the leakage rate is always positive, but less than 1.

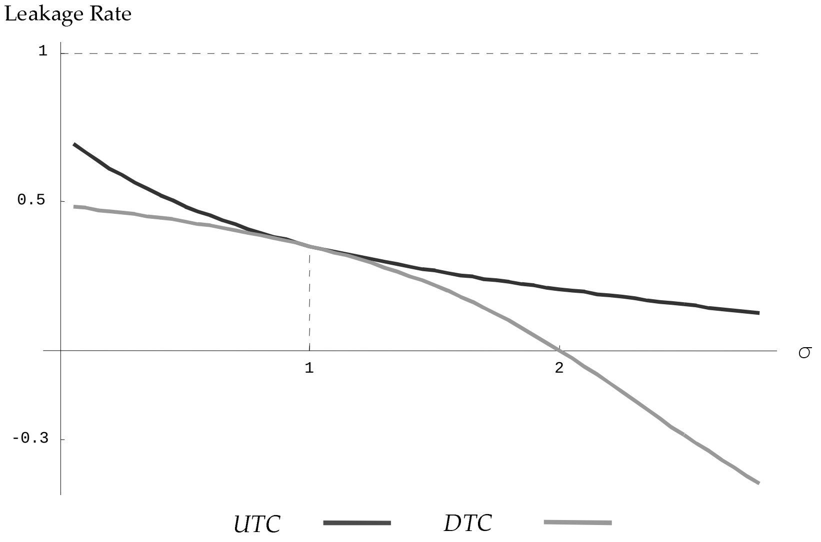

Figure 2.2: *Leakage rate under undirected (UTC) and directed (DTC) technical change*

2.3.2 Carbon leakage under directed technical change

In this section we focus on the central point of our analysis and derive our main results comparing the effects of an emission cap across regimes of technical change. We start by noting that allowing for directed technical change effectively provides the economy with an additional instrument to cope with the consequences of the introduction of a binding cap in the constrained country. Changes in the composition of technology may enable the unconstrained country to meet the increased demand for energy intensive goods while diverting less labour from its relatively more productive use in the Y_L sector. This is what we call the *induced-technology effect* of a unilateral emission constraint. We will show that this effect has the opposite sign to the terms-of-trade effect introduced above and hence tends to reduce carbon leakage.

We can compare the two versions of the model using the Le Chatelier principle (see e.g. Silberberg 1990). Taking the total differential of (2.16) and rearranging we can write the total effect of a change in the cap on emissions in the unconstrained country as:

$$\left.\frac{\partial L_E^u}{\partial L_E^c}\right|_{DTC} = \left.\frac{\partial L_E^u}{\partial L_E^c}\right|_{UTC} + \frac{\partial L_E^u}{\partial N}\frac{\mathrm{d}N}{\mathrm{d}L_E^c}, \tag{2.24}$$

where DTC indicates directed technical change and UTC undirected technical change. We can interpret this expression as saying that the overall effect of the cap when allowing for directed technical change (the left hand side) can be decomposed in a *terms-of-trade effect*, represented by the first term at the right-hand side, and an *induced-technology effect*. Whether these two effects act in the same direction or not ultimately determines under which regime we can expect leakage to be higher. In order to draw any conclusion, we need to sign the components of the above equation, thus getting the following result:

Proposition 2.3. *For $\sigma \neq 1$ carbon leakage will be smaller with directed technical change than with undirected technical change. For $\sigma = 1$ it will be identical across regimes.*

Proof. From Proposition 2.1 we know that $\partial L_E^u/\partial L_E^c|_{UTC} < 0$.

As for $\partial L_E^u/\partial N \cdot \mathrm{d}N/\mathrm{d}L_E^c$, consider first the case where $\sigma < 1$. From (2.20), it is immediate that $\mathrm{d}N/\mathrm{d}L_E^c < 0$. Moreover, from (2.16), when N (and hence $N^{1-\sigma}$) increases, L_E^u must decline to satisfy the equation, *cœteris paribus*. Thus, $\partial L_E^u/\partial N < 0$. Hence $\partial L_E^u/\partial N \cdot \mathrm{d}N/\mathrm{d}L_E^c > 0$.

Consider now $\sigma > 1$. By symmetric arguments, $\mathrm{d}N/\mathrm{d}L_E^c > 0$ and $\partial L_E^u/\partial N > 0$, implying once more $\partial L_E^u/\partial N \cdot \mathrm{d}N/\mathrm{d}L_E^c > 0$.

Finally, consider $\sigma = 1$. In this case N equals 1, irrespective of the value of S^w, hence $\mathrm{d}N/\mathrm{d}L_E^c = 0$. □

This result shows that the induced-technology effect works against the standard terms-of-trade effect of Proposition 2.1. It thus lowers the amount of carbon leakage that would occur if technical change were not directed. Figure 2.1 shows the two effects. The pure terms-of-trade effect can be read from the upwards shift of emissions from the dashed dark line (the model without a cap) to the dark solid line (the model with a cap and undirected technical change). The induced technology effect is summarized by the move from the solid black line to the light gray one (the model with a cap and directed technical change). Indeed, the amount of emissions is lower when technical change is directed, with the exception of the case where $\sigma = 1$. This is due to the fact that when $\sigma = 1$ our CES specification in (2.1) reduces to a Cobb-Douglas production function, in which case technical change will always be neutral to the inputs concerned.[19]

The key mechanism at work here, is that the type of technical change induced by the emission constraint proves to be always energy-saving. To show this, we first analyze how the composition of technology is affected by the introduction of the cap. Successively we address the interaction between changes in N and the level of σ, to explain the impact of technical change on the evolution of the relative factor shares in our economy.

The composition of technology evolves according to the relative profitability of R&D in the different sectors. As noted in section 2.2.2, the final effect of introducing a cap (i.e. a change in S^w) on relative profits depends both on changes in the relative market size and in relative prices. Climate policy reduces the amount of energy produced, and hence decreases the potential size of the market for new energy-complementing innovations. At the same time, it makes energy scarcer, thereby rising the price of energy and making an innovation for the energy intensive good more valuable. Whether the negative market size effect or the positive price effect dominates depends on σ, the elasticity of the relative demand for energy with respect to its relative price. Since in the long-run equilibrium the technology ratio is given by (2.20), we see that whenever $\sigma < 1$ the price effect dominates and the introduction of a cap induces an increase in N. When $\sigma > 1$ on the other hand, the market size effect dominates and N decreases. This relation between N and σ is plotted in Figure 2.3, where the dark line represents the ratio of technology under undirected technical change, while the lighter one depicts the case of directed technical change.

Recalling the expression for relative factor productivity from (2.15), we can

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[19] Notice that, formally, we would need share parameters summing up to one in (2.1) to obtain a constant-returns-to-scale Cobb-Douglas production function as ε (and hence σ) goes to 1.

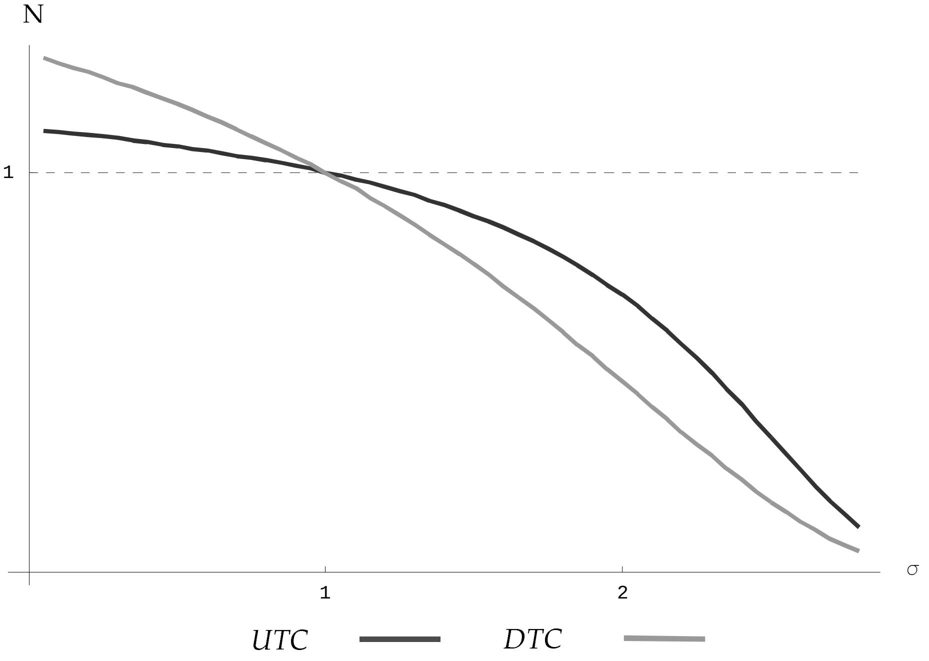

Figure 2.3: *Technology ratios (N) under undirected and directed technical change*

write the relative value share of energy to labour in country u as,

$$\frac{w_E E^u}{w_L L_L^u} \equiv wS^u = N^{(\sigma-1)/\sigma}(S^w)^{-1/\sigma}S^u.$$

We see that, for given N, the effect of the introduction of the cap (a decrease in S^w) is to unambiguously increase the share of energy in the unconstrained country. We know from the result in Proposition 2.1 that, when N is constant, leakage is always positive. Once we allow N to change in response to economic incentives, however, some form of induced energy-saving technical change occurs. The expression above shows how the effect of a change in the technology ratio on relative factor shares depends on σ. As discussed above, when $\sigma < 1$, N is higher than in the case of undirected technical change (see Figure 2.3). Thus, $N^{(\sigma-1)/\sigma}$ is lower, and the increase in the energy share due to the cap is counteracted by the induced change in technology. The same is true when $\sigma > 1$. In this case, however, both N and $N^{(\sigma-1)/\sigma}$ are below their baseline levels. Thus, irrespective of the level of σ, the effect of the induced change in technology ($N^{(\sigma-1)/\sigma}$) is to mitigate the terms-of-trade effect (which works through $(S^w)^{-1/\sigma}$). We can conclude that the technical change induced by the introduction of unilateral climate policy reduces the share of energy. Thus, technical change is endogenously energy-saving in our model. As shown in Proposition 2.3, directed technical change unambiguously leads to lower rates of carbon leakage.

The last question we want to address is whether the induced-technology effect we just highlighted can more than offset the terms-of-trade effect, and lead to a situation where carbon leakage is negative. Figure 2.1 shows that an affirmative answer is in order. Indeed, the curve representing emissions under directed technical change (the light curve) dips below the graph of the baseline case (the dashed curve), as σ gets larger. The following proposition makes it formal using a log-linearized version of our model, derived in Appendix B.2:[20]

Proposition 2.4. *When technical change is directed, carbon leakage due to a marginal tightening of the emission constraint will be positive for $\sigma < 2$, zero for $\sigma = 2$, and negative for $\sigma > 2$.*

Proof. In section B.3 of the Appendix we use a log-linearized version of the model to show that, around the equilibrium, we may write:

$$\frac{\widetilde{L_E^u}}{\widetilde{L_E^c}} = \frac{(\sigma - 2)\left((1-\eta)\,\phi + \chi \frac{L_E^c}{L_E^u}\right)}{(2-\sigma)\,(\eta\phi + \chi) + 1 - \phi}. \tag{2.25}$$

As discussed in Appendix B.3, a necessary condition for a stable equilibrium is that the term at the denominator be positive. Moreover, the second term in parenthesis at the numerator is always positive. Hence, around a stable equilibrium, we have $\widetilde{L_E^u}/\widetilde{L_E^c} \gtreqless 0$ whenever $\sigma \gtreqless 2$. □

This proposition shows that, when technical change is directed, the induced-technology effect can outweigh the terms-of-trade effect, provided that the elasticity of the relative demand for carbon-based energy is 'sufficiently large'. Whether σ larger than two is a plausible case, however, is difficult to assess from the available literature. In our model energy, E, implicitly stands for energy generated from fossil fuels rather than energy *tout-court*, as its generation directly causes the emissions of carbon dioxide. Where long-run own-price elasticities for 'broad' energy are estimated in the range 0.2 to 1.76 (see, e.g. Pindyck and Rotemberg 1983, Popp 2001, Gately and Huntington 2002), the estimates for fossil fuel products have values of up to 2.72 (see, e.g. Bates and Moore 1992, Espey 1998, Taheri and Stevenson 2002). Since σ can be interpreted as the price elasticity for *aggregated* fossil fuels, the former estimates

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[20] Although this proposition represents a local result, all our simulations confirm this pattern for the model in levels.

may provide a lower bound for σ while the latter may be seen as an upper bound. In this respect, a long-run value for the demand elasticity of fossil fuels of around 2 does not seem implausible.

2.4 Discussion and conclusions

The refusal of the United States to ratify the Kyoto Protocol is seen by many as a serious threat to the Protocol's effectiveness. If a coalition of technologically advanced (and hence fossil-fuel dependent) economies decides to voluntarily reduce its emissions of carbon dioxide, this will increase the price of dirty goods within this coalition. Unconstrained countries, such as the US, might benefit from increasing their production of dirty goods and exporting them to coalition members, thereby offsetting the decrease in emissions by the ratifying countries (carbon leakage).

However, environmental policy affects relative prices, and hence it modifies the relative profitability of inventing for the clean or dirty goods industry. The effects of changes in the direction of technical change on carbon leakage cannot be ignored. In this chapter we studied these effects taking explicitly into account that a technologically advanced country is outside the coalition. We presented a stylized theoretical model, which compares the results of a scenario where technology in the clean and dirty sectors is allowed to develop differently (directed technical change), to those derived from a model of 'traditional' endogenous technical change. We have shown that taking into account the endogeneity of the direction of technical change always leads to lower leakage rates than when this induced technology effect is ignored. We have also discussed the possibility that the sign of carbon leakage be reversed. When the elasticity of demand for carbon-based energy is sufficiently high, the change in technology due to the emission constraint is such that it becomes optimal for the unconstrained country to cut back on its emissions.

In order to emphasize the role of technical change on carbon leakage as clearly as possible, we had to abstract from several other mechanisms that play a role in determining the degree of leakage. Clearly, preferences, endowments, and production possibilities all play a role in determining the global effect of unilateral climate policy. However, by abstracting from these aspects, we were able to highlight the effect of profit incentives on innovation and ultimately on carbon leakage. Comforted by the empirical literature (see footnote 3), we believe that our results highlight a general and relevant mechanism: energy-saving technical change in the presence of climate policy. Indeed, when technology is given, the global ratio of energy to other inputs decreases (see Proposition 2.2), a result that has been found in virtually all of the CGE literature. This, in turn, induces energy-saving technological change, as we discussed in section 2.3.2. Relative to a situation without directed technical change, the global demand for carbon-based energy, the demand for fossil fuels in the unconstrained country, and hence the degree of carbon leakage, will all be lower.

Of course reality is more complicated than our stylized model. As mentioned in the introduction, there is at least one other important channel through which emissions leak from one country to the other. This we can broadly label the *energy-market channel*. When an emission cap is introduced, the price of carbon intensive fuels tends to decrease relative to cleaner ones, due to the decreased demand by constrained countries. As dirtier inputs become cheaper, countries outside the climate agreement tend to increase their demand, leading to additional carbon leakage.[21] The strength of this mechanism depends on the ease of inter-fuel substitution (whether it is technically possible to substitute natural gas for coal, for example), on the elasticity of supply of the different fuels, and on the possibility of trading different types of fuel internationally. The technical possibility to substitute one fuel for the other affects the size of the shift in demand following a change in the relative price. On the other hand, changes in relative prices also depend crucially on the decision of fuels producers whether to reduce supply as the price falls, and to what extent. Finally, if fuels (or some of them) are not easily traded internationally, the scope for substitution (and for carbon leakage through this channel) might also be limited.

The sensitivity of carbon leakage rates to changes in the key elasticities determining substitution, supply responses and trading flows have been comprehensively analyzed by Burniaux and Oliveira-Martins (2000). They conclude that the rate of leakage is higher, the higher the inter-fuel elasticity of substitution, the lower the elasticity of supply, and the higher the Armington elasticities among different fuels. Any of these elements could be the focus of possible extensions to our model. However, as long as the elasticities of

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[21] Given the differences in model assumptions for CGE models (see footnote 1), it is hard to say anything about the relative sizes of the energy market channel and the channel that works through trade in CO_2-intensive goods. According to Kuik (2005), CGE modelers seem to agree that the former channel is quantitatively the most important, at least in the short to medium term.

supply are not too small (as seems reasonable, given the long-run perspective of our analysis), and as long as trade in coal is limited (which seems sensible, given that coal is a very bulky fuel which requires expansive infrastructures and entails high transport costs), the degree of carbon leakage will be lower than 100%. Recalling the discussion above on energy-saving technical change, this suggests that also in this more complex framework, the same mechanism would be preserved and carbon leakage would be lower when the direction of technical change is endogenous.

Our results lend some support to the position of those who advocate the Kyoto Protocol, and other forms of unilateral climate policy as effective means to reduce carbon emissions. We have shown that the leakage rates that inform the current debate might prove overestimated, since the available quantitative literature neglects the role of endogeneity in the direction of technical change. As a consequence, unilateral climate policy might be more effective than generally claimed. Moreover, we also hint at the (theoretical) possibility that, when the demand for carbon-based energy is sufficiently elastic, ratifiers' efforts could be compounded by emission *reductions* by unconstrained countries.

Finally, we should note that the quantitative impact of the mechanisms we have highlighted in this chapter depends on the key elasticities of the model. Thus, our theoretical conclusions need to be assessed through quantitative methods, first and foremost using CGE models that incorporate directed technical change. The calibration of such a model, however, would require reliable sector-specific data on technical progress. Building such a model, and finding the necessary data, constitutes a formidable challenge for future research.

APPENDIX

B

ADDITIONAL PROOFS AND DERIVATIONS

B.1 Existence and stability of the equilibrium

The general equilibrium of the model requires that equilibrium on the goods market (18) and equilibrium on the market for innovations (21) are satisfied at the same time. Rearranging these expressions we get for the goods' market equilibrium:

$$N = \left(\frac{(\overline{L} - L_E)\phi^{\sigma}}{L_E^{\sigma(1-\phi)+\phi}} \right)^{\frac{1}{1-\sigma}} . \tag{GME}$$

and for the no-arbitrage equation in innovation:

$$N = \left(\frac{L_E^{\phi}}{\overline{L} - L_E} \right)^{\sigma-1} ; \tag{TECH}$$

We have the following result:

Proposition B.1. *For all* $\sigma \in \left(0, \frac{1+\phi}{\phi}\right)$ *there exists a unique stable (interior) equilibrium. When* $\sigma > \frac{1+\phi}{\phi}$*, the stable equilibrium collapses to the corner where* $L_E = 0$.

Proof. Here we sketch the proof without presenting the full (tedious) algebraic derivations.

We proceed to prove the proposition resorting to a graphical analysis, interpreting TECH and GME as lines in the (L_E, N) plane. We distinguish four different cases:

i. $\sigma \in (0,1)$. In this case both TECH and GME are downward sloping, and both have a vertical asymptote at $L_E = 0$ (See Figure B.1). Moreover, both cross the horizontal axis at $L_E = \overline{L}$. Since the limit of the ratio of TECH/GME as $L_E \to 0$, goes to 0, it is clear that GME is above TECH in a neighbourhood of $L_E = 0$. Analyzing the slope of both curves at $L_E \to \overline{L}$ reveals that, since the slope of TECH→ ∞ while GME's tends to 0, TECH is above GME as L_E approaches its maximum value ($\overline{L}$). This is enough to prove that there is at least one point of interception such that $L_E \in (0, \overline{L})$. Moreover, since GME is strictly convex while TECH is convex-concave with one inflection point, it follows that this equilibrium is unique.[1]

   Let us now consider the dynamics of the system outside the equilibrium. From the ratio of profits in the two sectors,

$$\pi = N^{-\frac{1}{\sigma}} S^{\frac{\sigma-1}{\sigma}},$$

   we see that when $\sigma < 1$ an increase in L_E above the level that satisfies the no -arbitrage condition $\pi = 1$ (that is, a point to the right of TECH), the relative profitability of innovation in the energy sector decreases. The subsequent adjustment requires an increase in innovation effort (and thus in the number of blueprints) in the labour-intensive sector, that is a decrease in N. The opposite is true for a decrease in the amount of labour employed in the energy sector.

   Since the composition of labour across sectors adjusts immediately, the dynamics of the system will be such that it will always move along the GME locus. As the graphical illustration in Figure B.1 makes clear, an equilibrium will be stable only if there GME is steeper that TECH. In the case depicted in the picture, the only stable equilibrium will be the interior one, since at the corner solution where $L_E = \overline{L}$ the TECH curve is steeper than the curve of GME.

ii. $\sigma \in (1,2]$. The analysis of this case is specular to the one above. In this case both curves are upward sloping and both have an asymptote at $L_E = \overline{L}$. Analyzing the relative positions and the curvatures, we can conclude once again that only one stable equilibrium exists and it is the interior one. The corner equilibrium at $L_E = 0$ is unstable.

iii. $\sigma \in \left(2, \frac{1+\phi}{\phi}\right)$. As in the previous case, both curves are upward sloping. However, the curvatures of the two curves change with σ, and when

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[1] The tedious algebraic derivations are omitted for brevity.

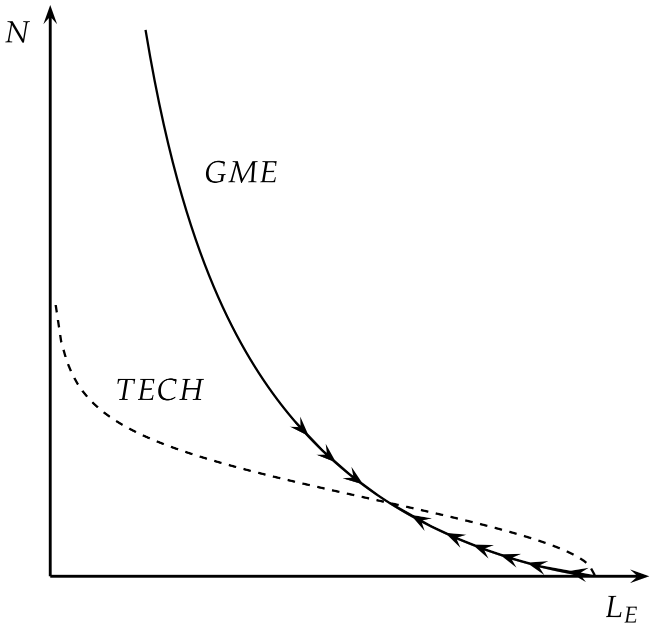

Figure B.1: *Stable Equilibrium when $\sigma < 1$*

$\sigma > 2$ GME falls below TECH in the neighbourhood of $\overline{L}$ so that the previous argument does not hold anymore. In order to prove that an equilibrium still exists we focus on a marginal change in σ, starting from $\sigma = 2$, for which case we know that an interior stable equilibrium exists at $L_E = \phi^{1/1-\phi}$. Simple comparative statics tell us that GME pivots clockwise around a point whose abscissa is $L_E = \frac{\phi}{1+\phi}\overline{L}$, whereas TECH pivots counter-clockwise around a point further to the right. Since $L_E = \frac{\phi}{1+\phi}\overline{L}$ is necessarily to the right of $L_E = \phi^{1/(1-\phi)}$ for $\overline{L} \geq 1$, it follows that the two curves will move in opposite directions, and they will cross even after the marginal change. The equilibrium point will shift to the left and towards the origin. We can iterate this argument as long as the curvatures are stable, tracing the stable equilibrium in its approach to the origin. When σ reaches the boundary point $\frac{1+\phi}{\phi}$, the interior equilibrium collapses to the origin which becomes the only stable equilibrium.

Since TECH is above GME around $L_E = 0$ and $L_E = \overline{L}$, and since we have just proved that they cross at least once, this implies that they will actually cross twice. Another equilibrium point indeed exists, but it can be shown to be unstable as there GME is flatter than TECH.

iv. $\sigma \in \left(\frac{1+\phi}{\phi}, +\infty\right)$. In this (degenerate) case the two curves only cross at the origin of the axes, thus the only equilibrium obtains where $L_E = 0$. As this case is not interesting for our analysis, we restrict our attention to the case where $\sigma \in \left(0, \frac{1+\phi}{\phi}\right)$.

This concludes our sketch of the proof. $\square$

B.2 The log-linearized model

The linearized version of the goods market equilibrium condition (2.16) reads:

$$(\sigma - 1)\,\widetilde{N} = \left[(1-\phi)\,\sigma + \eta\phi + \chi\right]\widetilde{L_E^u} + \left[(1-\eta)\,\phi + \chi\frac{L_E^c}{L_E^u}\right]\widetilde{L_E^c}, \tag{B.1}$$

where a tilde, $\widetilde{\ }$, over a variable denotes a small percentage change, and where we have used the following definitions:

$$\eta \equiv \frac{(L_E^u)^\phi}{(L_E^u)^\phi + (L_E^c)^\phi} \in (0,1), \text{ and } \chi \equiv \frac{L_E^u}{2\overline{L} - L_E^c - L_E^u}. \tag{B.2}$$

The percentage changes in L_E^u and L_E^c denote any marginal change in the respective variable. For example, a decrease in L_E^c (that is a $\widetilde{L_E^c} < 0$) from $L_E^c = L_E$ would represent the introduction of a marginal emissions cap in the country, while a decrease from any $L_E^c < L_E$ would represent any marginal tightening of an existing cap.

When we linearize the equilibrium condition for the market for innovations, (2.20), we find:

$$\widetilde{N} = (\sigma - 1)\left((1-\eta)\,\phi + \chi\frac{L_E^c}{L_E^u}\right)\widetilde{L_E^c} + (\sigma - 1)\,(\eta\phi + \chi)\,\widetilde{L_E^u}. \tag{B.3}$$

B.3 Appendix to Proposition 2.4

To find (2.25), substitute (B.3) into (B.1) and rewrite to find:

$$\frac{\widetilde{L_E^u}}{\widetilde{L_E^c}} = \frac{(\sigma - 2)\left((1-\eta)\,\phi + \chi\frac{L_E^c}{L_E^u}\right)}{(2-\sigma)\,(\eta\phi + \chi) + 1 - \phi}. \tag{B.4}$$

The denominator of this expression will be positive around any stable equilibrium. Indeed, the dynamics of the system require that at any stable equilibirum the slope of the goods market equilibrium condition be steeper than the

R&D equilibrium condition in the (L_E, N) space. The relevant slopes can be easily derived from (B.1) and (B.3). For $\sigma < 1$ the stability condition discussed above requires:

$$\left.\frac{\widetilde{N}}{\widetilde{L_E^u}}\right|_{GME} = \frac{(1-\phi)\sigma + \eta\phi + \chi}{\sigma - 1} < \left.\frac{\widetilde{N}}{\widetilde{L_E^u}}\right|_{R\&DE} = (\sigma - 1)(\eta\phi + \chi),$$

where the subscripts GME and $R\&DE$ indicate the goods markets and the R&D market equilibrium conditions, respectively. The sign of the inequality is reversed for the case when $\sigma > 1$. Since in both cases one can easily verify that the stability condition simplifies to

$$(2 - \sigma)\,(\eta\phi + \chi) + 1 - \phi > 0,$$

we have established our claim.

CHAPTER

THREE

THE DIRECTION OF TECHNICAL CHANGE IN CAPITAL-RESOURCE ECONOMIES[1]

The so-called *New Growth Theory* has formalized the determinants of productivity growth in economies where technological progress results from R&D activity. In this framework, horizontal (vertical) innovations improve the quantity (quality) of intermediate goods, and sustained growth obtains through *endogenous technical change* (ETC hereafter).[2]

In the field of resource economics, this generation of models has been exploited to provide new answers to an old question: the problem of sustaining growth in the presence of natural resource scarcity. A vast body of recent literature extends endogenous growth models to include natural resources as an essential input. The central aim of this literature is to determine whether technical progress is effective in ensuring sustained consumption over the long-run. This issue has been addressed in the endogenous technological change framework by Barbier (1999), Scholz and Ziemes (1999), Groth and Schou (2002), Grimaud and Rougé (2003), amongst others. These contributions present models where

(i) the direction of technical change is exogenous, and

(ii) technical progress is, explicitly or implicitly, resource-augmenting.[3]

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[1] This chapter is based on Di Maria and Valente (2006).

[2] This literature was started by the seminal works of Romer and (1986, 1987, 1990), Grossman and Helpman (1991), and Aghion and Howitt (1992).

[3] In section 2 we give a precise definition of implicit and explicit rates of resource-augmenting progress.

It should be stressed that assumption (ii) is crucial with respect to the sustainability problem: in the vast majority of growth models with exhaustible resources, ever-increasing consumption *requires* that the resource-augmenting progress strictly exceed the utility discount rate. The same reasoning underlies neoclassical models of optimal growth, where the rate of resource-saving progress is exogenous. Hence, most contributions in this field share the view that innovations increase, directly or indirectly, the productivity of natural resources. However, to our knowledge, the *existence* of purely resource-augmenting technical progress has not been micro-founded so far. Hence, one may object that the above models are conceptually biased in favor of sustainability: since technological progress may in principle be capital- rather than resource-augmenting, specifications (i)-(ii) might reflect a convenient, but strong assumption.

Recently, three important contributions by Daron Acemoglu (1998, 2002a, 2003a) developed models with *directed technical change* (DTC), where final output is obtained by means of two inputs, e.g. capital and labor, and technical progress may in principle be either labor- or capital-augmenting, or both. The respective rates of technical progress are determined by the relative profitability of developing factor-specific innovations, so that the direction of technical change is determined endogenously. Hence, DTC models can be considered an up-to-date formalization of the Hicksian notion of *induced innovations* - innovations directed at economizing the use of those factors that become expensive due to changes in their relative prices.[4]

This chapter investigates whether, and under what circumstances, technical change is endogenously directed towards resource-augmenting innovations. We tackle the issue in a multi-sector DTC framework, where exhaustible resources and accumulable man-made capital are both essential for production. This allows us to represent in more general terms the so-called *Capital-Resource Economy* - the central paradigm in resource economics since the pioneering contributions of Dasgupta and Heal (1974) and Stiglitz (1974). Elaborating on Acemoglu (2003a), we assume an R&D sector where capital- and resource-augmenting innovations increase the number of varieties of factor-specific intermediates. Our main result is that purely resource-augmenting technical change takes place along the balanced growth path: although the rate of capital-augmenting progress may be positive in the short run, it falls to zero as the economy approaches balanced growth. We thus provide a

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[4] See Hicks (1932, p. 124). Early formulations of the Hicksian notion of induced innovations include Kennedy (1964) and Drandakis and Phelps (1965).

possible micro-foundation for Capital-Resource models featuring resource-augmenting progress, in both the Solow-Ramsey and ETC frameworks: in this perspective, our results contradict the view that such models are too optimistic with respect to sustainability.

The plan of the chapter is as follows. Section 3.1 provides a classification of capital-resource economies in terms of technology specifications, and defines implicit and explicit rates of resource-augmenting technical progress. In section 3.2, we characterize the balanced growth path of the Capital-Resource economy under directed technical change, and derive the main results. Section 3.3 concludes.

3.1 Growth theory and resource economics

The much celebrated *Symposium on the Economics of Exhaustible Resources* is often recalled as the first close encounter between growth theory and resource economics. The Capital-Resource model of Dasgupta and Heal (1974), Solow (1974), and Stiglitz (1974) - i.e. an extended neoclassical growth model including exhaustible resources as a production factor - has since been considered a central paradigm in resource economics. More recently, several authors exploited new growth theories to analyze capital-resource economies with endogenous technical change: see e.g. Barbier (1999), Scholz and Ziemes (1999), Groth and Schou (2002), Grimaud and Rougé (2003), Bretschger and Smulders (2003).

A central aim of this literature is to determine whether, and under what circumstances, technical progress is effective in ensuring sustained consumption (Bretschger 2005). In this regard, the common denominator of both early and recent models is that a strictly positive rate of *resource-augmenting progress* is necessary to obtain non-declining consumption in the long run. We used italics in order to stress that the type of technological progress is a crucial element in Capital-Resource economies: from the perspective of sustainability, the 'direction' of technical change (whether it is resource-augmenting or capital-augmenting) is even more important than its 'nature' (i.e., whether it is exogenous or endogenous). To clarify this point, consider the following technologies:

$$Y(t) = F(K(t), M(t) R(t)), \tag{3.1}$$

$$Y(t) = A(t) K(t)^{\alpha_1} R(t)^{\alpha_2}, \tag{3.2}$$

where Y is output, K is man-made capital, R is an exhaustible resource extracted from a finite stock, F is concave and homogeneous of degree one, and $\alpha_1 + \alpha_2 \leq 1$. Technology (3.1) features an *explicit rate* of resource-augmenting progress equal to $\dot{M}/M$: the underlying assumption is that the economy develops resource-saving techniques that directly increase the productivity of R. Specification (3.2) combines the Cobb-Douglas form with disembodied technical progress: the Hicks neutral rate is equal to $\dot{A}/A$.

Firstly, consider the neoclassical framework: in this case, technology (3.1) exhibits $M(t) = e^{\eta t}$, with $\eta > 0$ exogenous and constant. Then, if cosumption obeys the standard Keynes-Ramsey rule, a necessary condition for sustained consumption in the long run is $\rho \leq \eta$, where ρ is the utility discount rate.[5] This is a generalization of a well-known result by Stiglitz (1974), who instead assumed technology (3.2) setting $A(t) = e^{\omega t}$ with $\omega > 0$ exogenous and constant. In this case, the necessary condition for non-declining consumption becomes $\rho \leq \omega/\alpha_2$. Hence, from the perspective of sustainability conditions, what is crucial is not the total effect of technical change on output levels (ω) but rather its resource-saving effect.[6] Indeed, technology (3.2) can be rewritten as $Y = K^{\alpha_1}\left(e^{(\omega/\alpha_2)t}R\right)^{\alpha_2}$, where (ω/α_2) is the *implicit rate* of resource-augmenting progress. This implies that assuming disembodied progress in association with a Cobb-Douglas form is not innocuous for the problem at hand: under specification (3.2), technical change is indirectly resource-augmenting.

The same reasoning applies with respect to ETC models, where $\dot{M}/M$ or $\dot{A}/A$ are determined endogenously by R&D activity. On the one hand, sustained consumption still requires that the resource-augmenting rate be at least equal to the discount rate: see e.g. Amigues, Grimaud, and Moreaux (2004). On the other hand, also in this framework, most technology specifications fall in either category (3.1) or (3.2). For example, technical progress is explicitly resource-augmenting in Amigues, Grimaud, and Moreaux (2004), whereas Aghion and Howitt (1998, Ch. 5), Barbier (1999), Scholz and Ziemes (1999), and Grimaud and Rougé (2003) assume variants of the Cobb-Douglas form (3.2).[7]

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[5] See Valente (2005). The same technology is assumed in Gaitan and Roe (2005).

[6] Actually, Stiglitz (1974) considers $Y = K(t)^{\alpha_1} R(t)^{\alpha_2} L(t)^{\alpha_3} e^{\omega t}$, where L is labor supplied inelastically. Results do not change under specification (3.2), which is chosen for expositional clarity.

[7] Bretschger and Smulders (2003) assume a peculiar CES technology where innovations are not directly resource-augmenting, but spillovers from capital-augmenting innovations directly affect resource productivity. In this case, resource-augmenting spillovers become necessary to sustain the economy, and the underlying logic is the same.

Hence, the common denominator of capital-resource models is that technological progress is, explicitly or implicitly, resource-augmenting by assumption. But is this assumption plausible? In principle, one might object, technical progress can be purely capital-augmenting instead. For example, suppose that $Y = \Upsilon(NK, R)$, where N represents purely capital-augmenting progress and Υ exhibits an elasticity of substitution different from unity. In this case, the production function does not allow for implicit resource-augmenting progress, and prospects for sustainability change dramatically. It follows from these considerations that a crucial issue is to determine whether (3.1)-(3.2) exhibit sound microeconomic foundations: if not, all mentioned contributions are conceptually biased in favor of sustainability because technologies (3.1) and (3.2) reflect a convenient, but strong assumption.

Tackling this issue requires assuming that the direction of technical change is endogenous. In the context of multi-sector economies, the DTC framework has been developed by Acemoglu (1998, 2002a, 2003a), who assumes that the rates of capital- and labor-augmenting technical change are respectively determined by the relative profitability of factor-specific innovations. In particular, Acemoglu (2003a) shows that a typical Capital-Labor economy exhibits purely labor-augmenting progress under directed technical change. In the field of environmental economics, models with DTC are analysed by André and Smulders (2006), Di Maria and Smulders (2004) and Di Maria and van der Werf (2005): Di Maria and Smulders (2004) study the role of endogenous technology in explaining cross-country differences in pollution and the pollution haven effect of international trade; Di Maria and van der Werf (2005) analyze carbon leakage effects under directed technical change considering clean versus dirty inputs; André and Smulders (2006) consider a Labor-Resource economy and compare equilibrium dynamics with recent international trends in energy supply and consumption. To our knowledge, however, the existence of purely resource-augmenting technical progress in a Capital-Resource Economy has not been micro-founded so far.

In order to address this point, this chapter studies whether, and under what circumstances, R&D activity is endogenously directed towards resource- augmenting innovations, given the alternative of developing capital-augmenting innovations. In particular, we assume a CES technology of the form $Y = F(NK, MR)$ with an elasticity of substitution below unity, and investigate the endogenous dynamics of N and M along the balanced growth path. The main difference with respect to Acemoglu (2003a) is that, since we substitute fixed labor with a resource flow extracted from an exhaustible stock, input units and factor rewards (that is, R and resource rents) are necessarily time-varying: the extracting sector exploits the natural stock over an infinite time-horizon, and resource prices therefore obey the Hotelling rule (Hotelling 1931). This implies that we cannot translate *a priori* the result of 'purely labor-augmenting progress' of Acemoglu (2003a) into 'purely resource-augmenting progress' in our model, until we prove that the Hotelling rule fully supports the time-paths of intermediate goods prices compatibly with balanced growth. We will show that this is actually the case in our model.

3.2 The model

The supply-side of the economy consists of five sectors: (*i*) the final sector assembles capital-intensive and resource-intensive goods ($\tilde{K}$ and $\tilde{R}$). These goods are produced by (*ii*) competitive firms, using n varieties of capital-specific intermediates ($y^K_{(j)}$ with $j \in (0, n]$), and m varieties of resource-specific intermediate goods ($y^R_{(j)}$ with $j \in (0, m]$), respectively. Factor-specific intermediates are supplied by (*iii*) monopolists producing $y^K_{(j)}$ by means of available man-made capital (K), and producing $y^R_{(j)}$ by means of extracted resource (R); the resource is supplied by (*iv*) an extracting sector that exploits a finite stock (H) of exhaustible natural capital. Finally, (*v*) the R&D sector consists of firms that develop capital-augmenting innovations (blueprints that increase n) and firms that develop resource-augmenting innovations (blueprints that increase m). The productivity of R&D firms depends on the amounts of 'scientists' employed in the two subsectors (S^K and S^R, respectively).

Our specifications follow the analysis in Acemoglu (2003a): aggregate output Y equals

$$Y = F\left(\tilde{K}, \tilde{R}\right) = \left[\gamma \tilde{K}^{\frac{\sigma-1}{\sigma}} + (1-\gamma)\, \tilde{R}^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{3.3}$$

where $\gamma \in (0,1)$ is a weighting parameter, and σ is the (constant) elasticity of substitution between $\tilde{K}$ and $\tilde{R}$. From the point of view of resource economics and sustainability theory, the interesting case is that featuring $\sigma < 1$: when resource-intensive goods are essential, natural resource scarcity binds the economy over the entire time-horizon considered, $t \in [0, \infty)$.

Competitive firms produce $\tilde{K}$ and $\tilde{R}$ by means of factor-specific intermediates, $y^K_{(j)}$ and $y^R_{(j)}$. In each instant t, there are $n\,(t)$ varieties of $y^K_{(j)}$ and $m\,(t)$ varieties of $y^R_{(j)}$, and factor-intensive goods are produced according to technologies

$$\tilde{K} = \left[\int_0^n \left(y_{(j)}^K \right)^\beta dj \right]^{\frac{1}{\beta}} \text{ and } \tilde{R} = \left[\int_0^m \left(y_{(j)}^R \right)^\beta dj \right]^{\frac{1}{\beta}}, \tag{3.4}$$

where $\beta \in (0, 1)$. Intermediates $y_{(j)}^K$ and $y_{(j)}^R$ are supplied by monopolists who hold the relevant patent, and exploit linear technologies

$$y_{(j)}^K = K^{(j)} \text{ and } y_{(j)}^R = R^{(j)}, \tag{3.5}$$

where $K^{(j)}$ indicates units of man-made capital used to produce $y_{(j)}^K$, and $R^{(j)}$ indicates units of resource used to produce $y_{(j)}^R$.[8] The value of patents held by monopolists equals the present-value stream of instantaneous profits implied by capital- and resource-augmenting innovations (π^K and π^R, respectively), discounted by the interest rate r and the assumed obsolescence (depreciation) rate δ:

$$V^i(t) = \int_t^\infty \pi^i(v) e^{-\int_t^v (r(\omega)+\delta)d\omega} dv, \text{ with } i = K, R. \tag{3.6}$$

For future reference, on the basis of (3.6) we can define an *index of relative profitability* of the two types of innovations as

$$\Delta(t) \equiv \int_t^\infty \frac{n(v)\,\pi^K(v)}{m(v)\,\pi^R(v)} dv. \tag{3.7}$$

Denoting aggregate capital by $K(t)$, and the total amount of extracted resource by $R(t)$, market-clearing requires

$$\int_0^{n(t)} K^{(j)}(t)\,dj = K(t) \text{ and } \int_0^{m(t)} R^{(j)}(t)\,dj = R(t). \tag{3.8}$$

For simplicity, we assume that the capital stock, K, does not depreciate. The amount of resource R is supplied by the extracting sector. Denoting the interest rate by r and the resource price by q, the present-discounted value of future profits for the extracting sector is

$$\int_0^\infty q(t) R(t) e^{-\int_0^t r(v)dv} dt, \tag{3.9}$$

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[8] It is worth noting, at this point, the role of symmetric technologies for factor-intensive goods and intermediates. In this chapter, we are interested in the direction of technical change as driven by the 'general nature' of primary inputs, i.e. reproducibility (of man-made capital) versus exhaustibility (of the natural resource). Symmetric technologies in (3.4) and (3.5) are essential to this aim: assuming factor-specific elasticities - setting e.g. $\beta^K \neq \beta^R$ in (3.4) - or different marginal costs for monopolists in (3.5) would create trivial distortions in the relative profitability of factor-specific innovations, without addressing the main issue.

where we have ruled out extraction costs for simplicity. Assuming that the natural resource is exhaustible, extraction plans face the following constraints:

$$\dot{H}(t) = -R(t) \text{ and } \int_0^\infty R(t)\, dt \le H(0), \tag{3.10}$$

where H indicates the resource stock.

In this model, the source of endogenous growth is given by increases in the number of varieties: $\dot{n}(t) > 0$ corresponds to capital-augmenting technical change, and $\dot{m}(t) > 0$ corresponds to resource-augmenting technical change. Increases in varieties are obtained through R&D activity. In this sector, free-entry conditions ensure that firms make zero extra profits. Firms developing capital- and resource-augmenting innovations employ S^K and S^R scientists, respectively. An important assumption is that scientists are fully mobile between the two types of firms: in each instant, scientists can be reallocated between capital- and resource-augmenting activity, according to the relative profitability of the two types of innovations. The technologies for invention are represented by

$$\dot{n}/n = b^K S^K \phi\left(S^K\right) - \delta, \tag{3.11}$$

$$\dot{m}/m = b^R S^R \phi\left(S^R\right) - \delta, \tag{3.12}$$

where $\delta > 0$ is the obsolescence rate of both innovations, and b^K and b^R are constant productivity indices. The number of scientists affects the productivity of R&D firms through $S^K\phi\left(S^K\right)$ and $S^R\phi\left(S^R\right)$. The function $\phi(.)$ is assumed to be continuously differentiable and strictly decreasing, such that $\partial\left(S^i\phi\left(S^i\right)\right)/\partial S^i > 0$. On the one hand, assuming $\phi'(.) < 0$ captures *crowding effects* among scientists (when more scientists are employed in one sector, the productivity of each declines); on the other hand, the net effect of a marginal increase in employed scientists on the rate of innovation is positive: $\dot{S}^K > 0$ increases $\dot{n}/n$. Crowding effects are not internalized by R&D firms, so that $b^R\phi\left(S^R\right)$ and $b^K\phi\left(S^K\right)$ are taken as given when firms compete for hiring scientists. We further assume that the number of existing scientists (S) suffices to have a stationary mass of varieties ($\dot{m} = \dot{n} = 0$):

$$S > \bar{S}^K + \bar{S}^R \tag{3.13}$$

where $\bar{S}^K$ and $\bar{S}^R$ satisfy $b^K\bar{S}^K\phi\left(\bar{S}^K\right) = \delta$ and $b^R\bar{S}^R\phi\left(\bar{S}^R\right) = \delta$ by definition.

To close the model, we consider a representative agent with logarithmic instantaneous preferences, and a constant utility discount rate $\rho > 0$. Assuming unit mass population, and denoting aggregate consumption by C, an optimal consumption path is a plan $\{C(t)\}_{t=0}^{\infty}$ that maximizes

$$\int_0^\infty \log C(t)\, e^{-\rho t} dt, \tag{3.14}$$

subject to the aggregate wealth constraint

$$\dot{K} = rK + qR + wS - C, \tag{3.15}$$

where rK is capital income (r is the marginal reward of capital), qR represents resource rents, and w is the wage rate for scientists, so that wS is total labor income.[9] Our results do not change if we substitute logarithmic preferences with a CRRA instantaneous utility function: in (3.14), the intertemporal elasticity of substitution is set equal to one to simplify the exposition.

3.2.1 Equilibrium

Denote by p^K and p^R the prices of capital- and resource-intensive goods ($\tilde{K}$, $\tilde{R}$), and the prices of factor-specific intermediates ($y_{(j)}^K$, $y_{(j)}^R$) by $\chi_{(j)}^K$ and $\chi_{(j)}^R$, respectively. An equilibrium of the economy is defined by a vector of price time-paths

$$\left\{ p^K, p^R, \chi_{(j)}^K \Big|_{j=0}^{n}, \chi_{(j)}^R \Big|_{j=0}^{m}, r, q, w \right\}_{t=0}^{\infty}$$

and a sequence of allocations

$$\left\{ \tilde{K}, \tilde{R}, y_{(j)}^K \Big|_{j=0}^{n}, y_{(j)}^R \Big|_{j=0}^{m}, K, R, S^K, S^R, C \right\}_{t=0}^{\infty},$$

such that, for given prices in the respective sectors: consumption and investment plans maximize (3.14) subject to (3.15); allocations of capital- and resource-intensive goods maximize final sector profits; allocations of capital- and resource-specific intermediates maximize profits

$$p^K \tilde{K} - \int_0^n \chi_{(j)}^K y_{(j)}^K dj \quad \text{and} \quad p^R \tilde{R} - \int_0^m \chi_{(j)}^R y_{(j)}^R dj \tag{3.16}$$

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[9] To see why this is the case, consider total wealth as the sum of the value of capital and of the resource stock $W = K + qH$. The budget constraint of the representative consumer is: $\dot{W} = rK + \dot{q}H + wS - C$. Equation (3.15) follows immediately from substituting $\dot{W} = \dot{K} + \dot{q}H + q\dot{H}$ in the budget constraint, and recalling that $\dot{H} = -R$. See for example, Groth and Schou (2005).

subject to (3.4); allocations of capital and resource inputs maximize monopolistic instantaneous profits

$$\pi^K_{(j)} = \left[\chi^K_{(j)} - r\right] y^K_{(j)} \quad \text{and} \quad \pi^R_{(j)} = \left[\chi^R_{(j)} - q\right] y^R_{(j)} \tag{3.17}$$

subject to demand schedules for $y^K_{(j)}$ and $y^R_{(j)}$; extracted resource flows maximize (3.9) subject to (3.10); scientist allocations S^K and S^R imply zero profits for all R&D firms; and all markets clear.

Setting aggregate output as the numeraire good, the equilibrium is characterized by the following relations. First order conditions for the final sector read

$$p^K = \gamma \left(Y/\tilde{K}\right)^{\frac{1}{\sigma}} \quad \text{and} \quad p^R = (1-\gamma)\left(Y/\tilde{R}\right)^{\frac{1}{\sigma}}, \tag{3.18}$$

with price-index normalization implying

$$\left[\gamma^\sigma \left(p^K\right)^{1-\sigma} + (1-\gamma)^\sigma \left(p^R\right)^{1-\sigma}\right]^{\frac{1}{\sigma-1}} = 1. \tag{3.19}$$

Next, maximization of (3.16) subject to (3.4) implies demand schedules for intermediates

$$y^K_{(j)} = \left(\chi^K_{(j)}/p^K\right)^{\frac{1}{\beta-1}} \tilde{K} \quad \text{and} \quad y^R_{(j)} = \left(\chi^R_{(j)}/p^R\right)^{\frac{1}{\beta-1}} \tilde{R}. \tag{3.20}$$

Monopolists producing factor-specific intermediates maximize (3.17) taking schedules (3.20) as given, obtaining first order conditions

$$\chi^K_{(j)} = r\beta^{-1} \quad \text{and} \quad \chi^R_{(j)} = q\beta^{-1}. \tag{3.21}$$

Expressions (3.21) imply that equilibrium instantaneous profits $\pi^K_{(j)}$ and $\pi^R_{(j)}$ are invariant across varieties: from the market clearing condition (3.8), we have

$$y^K_{(j)} = K^{(j)} = K/n \quad \text{and} \quad y^R_{(j)} = R^{(j)} = R/m, \tag{3.22}$$

so that equilibrium profits read

$$\pi^K = r(1-\beta)(n\beta)^{-1} K \quad \text{and} \quad \pi^R = q(1-\beta)(m\beta)^{-1} R. \tag{3.23}$$

From (3.23), we can substitute instantaneous profits and obtain equilibrium present-value streams as

$$V^K(t) = \frac{1-\beta}{\beta}\int_t^\infty \frac{K(v)}{n(v)} r(v)\, e^{-\int_t^v (r(\omega)+\delta)d\omega} dv, \tag{3.24}$$

$$V^R(t) = \frac{1-\beta}{\beta}\int_t^\infty \frac{R(v)}{m(v)} q(v)\, e^{-\int_t^v (r(\omega)+\delta)d\omega} dv, \tag{3.25}$$

As regards resource extraction, maximizing (3.9) subject to (3.10) yields the standard Hotelling rule

$$\dot{q}/q = r, \tag{3.26}$$

which implicitly defines an optimal depletion path.

In the R&D sector, the value of the marginal innovation in the two types of firms is respectively given by $b^K\phi\left(S^K\right)nV^K$ and $b^R\phi\left(S^R\right)mV^R$. In general, the equilibrium wage rate of scientists is given by

$$w = \max\left\{b^K\phi\left(S^K\right)nV^K, b^R\phi\left(S^R\right)mV^R\right\}, \tag{3.27}$$

which takes into account possible corner solutions. When equilibrium levels of S^K and S^R are both positive, we have $b^K\phi\left(S^K\right)nV^K = b^R\phi\left(S^R\right)mV^R$ and $S^K + S^R = S$, so that

$$\frac{nV^K}{mV^R} = \frac{b^R\phi\left(S - S^K\right)}{b^K\phi\left(S^K\right)} \tag{3.28}$$

at any instant in which both types of innovations are developed. Finally, consumption dynamics follow the standard Keynes-Ramsey rule

$$\dot{C}/C = r - \rho. \tag{3.29}$$

Integrating (3.4) using (3.22) we obtain

$$\tilde{K} = n^{\frac{1-\beta}{\beta}}K \quad \text{and} \quad \tilde{R} = m^{\frac{1-\beta}{\beta}}R. \tag{3.30}$$

Substituting (3.30) in (3.20), and using conditions (3.21) we obtain

$$r = \beta p^K n^{\frac{1-\beta}{\beta}} \quad \text{and} \quad q = \beta p^R m^{\frac{1-\beta}{\beta}}. \tag{3.31}$$

In order to characterize dynamics, it is useful to define elasticity-adjusted indices of intermediates varieties as $N \equiv n^{\frac{1-\beta}{\beta}}$ and $M \equiv m^{\frac{1-\beta}{\beta}}$. From (3.30) we can thus rewrite aggregate output $Y = F(\tilde{K}, \tilde{R})$ in equilibrium as

$$Y = F\left(NK, MR\right) = \left[\gamma\left(NK\right)^{\frac{\sigma-1}{\sigma}} + \left(1-\gamma\right)\left(MR\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}. \tag{3.32}$$

Expression (3.32) clarifies the role of innovations in determining the rates of technical progress through expansions of intermediates varieties. For this reason we will refer to $\dot{N}/N$ and $\dot{M}/M$ as the (net) rates of capital-augmenting and resource-augmenting technical progress.

Since F is homogeneous of degree one, we can express the augmented output-resource ratio Y/MR in intensive form as follows,

$$Y/MR = f\left(x\right) = \left[1 - \gamma\left(1 - x^{\frac{\sigma-1}{\sigma}}\right)\right]^{\frac{\sigma}{\sigma-1}}. \tag{3.33}$$

Where we have indicated the production function in intensive form as $f(x)$ and defined the augmented capital-resource ratio,

$$x \equiv \frac{NK}{MR}. \tag{3.34}$$

Rewriting (3.18) using $f(x)$, yields:

$$\begin{aligned} p^K &= f'_x(x) = \gamma \left(f(x)/x \right)^{\frac{1}{\sigma}}, && (3.35) \\ p^R &= f(x) - f'_x(x)\, x = (1-\gamma)\left(f(x) \right)^{\frac{1}{\sigma}}; && (3.36) \end{aligned}$$

from which we can also derive the following expression for the relative capital share,

$$\xi \equiv \frac{rK}{qR} = \frac{\gamma}{1-\gamma} x^{\frac{\sigma-1}{\sigma}} \Rightarrow \partial \xi / \partial x < 0. \tag{3.37}$$

Moreover, note that p^K and p^R can be expressed as[10]

$$\begin{aligned} p^K(x) &= \left[\gamma^\sigma + x^{\frac{1-\sigma}{\sigma}} (1-\gamma)\gamma^{\sigma-1} \right]^{1/(\sigma-1)} && \Rightarrow \partial p^K / \partial x < 0, \text{ and} && (3.38) \\ p^R(x) &= \left[x^{\frac{\sigma-1}{\sigma}} \gamma^\sigma (1-\gamma)^{\sigma-1} + (1-\gamma)^\sigma \right]^{1/(\sigma-1)} && \Rightarrow \partial p^R / \partial x > 0, && (3.39) \end{aligned}$$

where the sign of both derivatives follows from $\sigma < 1$. When capital- and resource-intensive goods are complements, an increase in the augmented capital-resource ratio (x) leads to a decrease in the relative capital share (ξ), a decrease in the price of capital-intensive goods (p^K), and an increase in the price of resource-intensive goods (p^R). On the basis of the above relations, the dynamics of x can be expressed in terms of the two indices of intermediates varieties:

Lemma 1. *In equilibrium, the dynamics of the augmented capital-resource ratio are described by*

$$\dot{x} = \sigma \frac{f(x)}{f'_x(x)} \left(f'_x(x)\, \beta N - \frac{\dot{M}}{M} \right). \tag{3.40}$$

Proof. Differentiate (3.36) to get

$$\frac{\dot{p}^R}{p^R} = \frac{\dot{x} f'_x(x)}{\sigma f(x)}. \tag{3.41}$$

---

[10] Expressions (3.38)-(3.39) can be derived from price-index normalization. Multiplying both sides of (3.19) by p^R gives $p^R = \left[\gamma^\sigma \left(p^K/p^R \right)^{\sigma-1} + (1-\gamma)^\sigma \right]^{1/(\sigma-1)}$. Substituting from (3.18) the price ratio $p^K/p^R = \gamma(1-\gamma)^{-1} x^{-(1/\sigma)}$ yields (3.39). Symmetric steps yield (3.38).

From (3.31) and (3.35), the interest rate equals

$$r = f'_x(x)\,\beta N. \tag{3.42}$$

Differentiating the expression for q in (3.31) we obtain $\dot{q}/q = (\dot{p}^R/p^R) + (\dot{M}/M)$. Substituting $\dot{p}^R/p^R$ from (3.41), $\dot{q}/q = r$ from (3.26), and the interest rate from (3.42), we obtain the dynamic law (3.40). □

Equation (3.40) shows that the augmented capital-resource ratio increases (decreases) when the interest rate exceeds (falls short of) the net rate of resource -augmenting technical change, $\dot{M}/M$. Neoclassical and ETC models with purely resource-augmenting progress can be seen as particular cases of this general rule: the basic difference here is that N and $\dot{M}/M$ are both endogenous. If we normalize $N = 1$ and assume $\dot{M}/M = \eta > 0$ (exogenous constant) in equation (3.40) we have the dynamic rule for the capital-resource ratio in the Ramsey model with exogenous progress (see Valente 2005, eq.16). Alternatively, normalising $N = 1$ and keeping $\dot{M}/M$ endogenously determined by R&D activity, we have purely resource-augmenting progress *à la* Amigues, Grimaud, and Moreaux (2004).

3.2.2 Balanced Growth Path

We begin our characterization of long-run equilibria by considering possible Balanced Growth Paths (BGPs). We will denote by y_∞ the limit $\lim_{t\to\infty} y(t)$, and by y_* the value of y along the balanced growth path, for any variable y.

Following the standard definition, a BGP equilibrium features $(\dot{C}/C)_\infty = g_*$ with g_* finite and constant. We now show that $(\dot{C}/C)_\infty = g_*$ implies a constant augmented capital-resource ratio in the long run. Starting from (3.40), we have three possible cases regarding the asymptotic value of x: in general, the augmented capital-resource ratio may approach zero ($x_\infty = 0$), diverge to infinity ($x_\infty = \infty$), or converge to a positive steady-state value, $x = \bar{x}$ with $\bar{x} > 0$ a finite constant. The next Proposition establishes that only the third case ($x = \bar{x}$) is compatible with BGP.

Proposition 3.1. *If $(\dot{C}/C)_\infty = g_*$ finite and constant, then $x_\infty = \bar{x} > 0$ finite and constant.*

Proof. The proof builds on the fact that $x_\infty = 0$ and $x_\infty = \infty$ have the following implications:

$$x_\infty = 0 \Rightarrow S^K_\infty = S \Rightarrow (\dot{n}/n)_\infty = b^K S\phi(S) - \delta \Rightarrow (\dot{m}/m)_\infty = -\delta, \tag{3.43}$$

$$x_\infty = \infty \Rightarrow S^K_\infty = 0 \Rightarrow (\dot{n}/n)_\infty = -\delta \Rightarrow (\dot{m}/m)_\infty = b^R S\phi(S) - \delta, \tag{3.44}$$

Expressions (3.43) and (3.44) are proved in the Appendix, using the index of relative profitability defined in (3.7). From (3.43), if the augmented capital-resource ratio approaches zero, all scientists are employed in developing capital-augmenting innovations, and the number of resource-specific intermediates m will approach zero due to depreciation. From (3.44), in the opposite case, x diverges to infinity, all scientists are employed in resource-augmenting innovations, and the number of capital-specific intermediates will approach zero in the long run. But neither (3.43) nor (3.44) are compatible with BGP. Recalling the Keynes-Ramsey rule (3.29), having $(\dot{C}/C)_\infty = g_*$ requires a constant interest rate. From (3.31), $\dot{r}_\infty = 0$ in turn requires

$$\lim_{t\to\infty} \frac{\dot{p}^K(t)}{p^K(t)} = -\lim_{t\to\infty} \frac{\dot{N}(t)}{N(t)}, \tag{3.45}$$

which implies that $\dot{p}^K_\infty$ and $\dot{N}_\infty$ are either both zero or of opposite sign. First, suppose that $\dot{p}^K_\infty > 0$ and $\dot{N}_\infty < 0$: from (3.38), $\dot{p}^K_\infty > 0 \Rightarrow \dot{x}_\infty < 0 \Rightarrow x_\infty = 0$; but then, expression (3.43) would imply $\dot{N}_\infty > 0$, which contradicts the supposition. Second, suppose that $\dot{p}^K_\infty < 0$ and $\dot{N}_\infty > 0$: from (3.38), $\dot{p}^K_\infty < 0 \Rightarrow \dot{x}_\infty > 0 \Rightarrow x_\infty = \infty$; but then, expression (3.44) would imply $\dot{N}_\infty < 0$, which contradicts the supposition. Hence, in order to have a constant interest rate we need $\dot{p}^K_\infty = \dot{N}_\infty = 0$, which implies $\dot{x}_\infty = 0$ from (3.38). Consequently, if the economy converges to BGP, $x_\infty = \bar{x} > 0$ with $\bar{x}$ finite and constant. □

Proposition 3.1 shows that balanced growth requires $\dot{x}_\infty = 0$ and $\dot{N}_\infty = \dot{n}_\infty = 0$, so that if the economy approaches a BGP equilibrium we have $x_\infty = x_*$ and $N_\infty = N_*$. A constant level of N means that the *net* growth rate of capital-specific intermediates is zero. Note that, due to obsolescence ($\delta > 0$), $\dot{n}_\infty = 0$ does not imply zero R&D activity in capital-augmenting innovations: a positive number of scientists ($S^K_\infty > 0$) must work in the capital-augmenting sector in order to keep n, the number of capital-specific intermediates, constant over time. More important,

Proposition 3.2. *Convergence to BGP implies purely resource-augmenting technical change, with the net rate $\dot{M}/M$ converging to the equilibrium interest rate:*

$$\lim_{t\to\infty} \frac{\dot{N}(t)}{N(t)} = 0 \quad \textit{and} \quad \lim_{t\to\infty} \frac{\dot{M}(t)}{M(t)} = r_* = f'_x(x^*)\,\beta N^*. \tag{3.46}$$

Proof. From Proposition 3.1, balanced growth requires $\dot{p}^K_\infty = \dot{N}_\infty = \dot{x}_\infty = 0$. Substituting (3.42) in (3.40) and setting $\dot{x}_\infty = 0$ completes the proof. □

This is the main result of the chapter. The intuition for (3.46) is that balanced growth requires constant prices of both capital- and resource-intensive goods ($\dot{p}^K_\infty = \dot{x}_\infty = 0$ implies, from (3.36), that $\dot{p}^R_\infty = 0$ as well). On the one hand, since the price of resource-intensive goods is proportional to q/M - from (3.31) - balanced growth is possible only if the net rate of resource-saving progress exactly offsets the growth in the resource price. On the other hand, efficient exploitation of the exhaustible resource requires the resource price to grow at a rate equal to r by virtue of the Hotelling rule (3.26), implying $(\dot{M}/M)_\infty = r_*$.[11] Hence, the BGP equilibrium of the economy is characterized by the following dynamics:

$$\begin{aligned}
\dot{\tilde{K}}_*/\tilde{K}_* &= \dot{\tilde{R}}_*/\tilde{R}_* = \dot{Y}_*/Y_* = \dot{C}_*/C_* = r_* - \rho, && (3.47)\\
\dot{R}_*/R_* &= -\rho, && (3.48)\\
\dot{m}_*/m_* &= \beta\left(1-\beta\right)^{-1} r_*, && (3.49)\\
\dot{n}_*/n_* &= 0, && (3.50)\\
\dot{\pi}^K_*/\pi^K_* &= r_* - \rho, && (3.51)\\
\dot{\pi}^R_*/\pi^R_* &= \frac{1-2\beta}{1-\beta} r_* - \rho, && (3.52)
\end{aligned}$$

Substituting (3.51)-(3.52) in (3.24)-(3.25) we obtain the BGP values of patents: if the economy converges to balanced growth, we have

$$\begin{aligned}
V^K(t) &= \frac{(1-\beta)\, r_*}{\beta\,(\delta+\rho)\, n_*} \cdot K(t), && (3.53)\\
V^R(t) &= \frac{1-\beta}{\beta\left(\frac{\beta}{1-\beta} r_* + \delta + \rho\right)} \cdot \frac{q(t)\, R(t)}{m(t)}, && (3.54)
\end{aligned}$$

for any sufficiently large t. Equations (3.53)-(3.54) imply that both nV^K and mV^R will grow at the balanced rate $r_* - \rho$. Finally, equilibrium in the 'labor market for scientists' requires

$$b^K \phi\left(S^K_*\right) n_* V^K(t) = b^R \phi\left(S^R_*\right) m(t)\, V^R(t), \qquad (3.55)$$

---

[11] Formally, this reasoning provides an equivalent proof of Proposition 3.2: differentiating q from (3.31) and substituting the Hotelling rule $\dot{q}/q = r$, we obtain $r = (\dot{p}^R/p^R) + (\dot{M}/M)$. Taking the limit and substituting $\dot{p}^R_\infty = 0$ we obtain (3.46).

where $S_*^K = \bar{S}^K$ and $S_*^R = S - \bar{S}^K$.

Since $f_x'(.)$ is homogeneous of degree zero and $\partial\left(S^K\phi\left(S^K\right)\right)/\partial S^K > 0$, a unique couple of values $(x_*, S_*^K = \bar{S}^K)$ satisfies $r_* = f_x'(x^*)\,\beta N^*$ with N^* determined by S_*^K, and the BGP equilibrium is therefore unique. As regards other possible long-run equilibria, the BGP described above is the only possible long-run equilibrium provided that the economy exhibits non-cyclical paths: in this case, $(\dot{C}/C)_\infty = \infty$ cannot be an equilibrium. The proof is identical to that in Acemoglu (2003), and is reported in the Appendix.

As regards the dynamic stability of the BGP equilibrium, in the Appendix we show that linearizing the five-by-five system of differential equations describing the dynamics of the model, we can show that the system is locally stable. In particular, we show that the Jacobian matrix obtained from the linearization procedure, **J**, evaluated at the steady state $x_*, N_*, S_*^K, C_*/K_*, R_*/H_*$, has three positive and two negative eigenvalues.

3.2.3 Remarks

We have formalized directed technical change in a Capital-Resource economy by extending the benchmark DTC model of Acemoglu (2003a) to include natural capital. Acemoglu (2003a) assumes that final output is a combination of capital-intensive and *labor*-intensive goods, and shows that, when both goods are essential, there exists a unique balanced growth path with purely labor-augmenting technical change. In this chapter, raw labor inputs are replaced by resource flows extracted from an exhaustible natural stock. We have shown that the equilibrium time-path of resource prices, which obeys the standard Hotelling rule, fully supports the time-path of intermediate goods prices that is compatible with the BGP equilibrium. In particular, the asymmetric role of the two types of innovation follows immediately from equilibrium conditions (3.31). Balanced growth typically requires a constant interest rate (the rental price of capital): given that q (the price of natural resource) must grow forever, fulfilling (3.31) for given prices p^K and p^R requires differentiated innovation rates $\dot{m}/m \neq \dot{n}/n$. As a consequence, in our Capital-Resource economy we were able to find a BGP equilibrium, which is locally stable, and features purely resource-augmenting technical change.

From Proposition 3.2, the asymptotic rate of resource-augmenting progress exactly equals the interest rate. A similar result can be obtained in the neoclassical framework, but following an inverse logic: for a given exogenous rate of resource-augmenting technical progress η, the marginal product of capital converges to η, determining constant factor shares in the long run (Stiglitz 1974). In the present context, instead, the rate of technical change is endogenous and its behavior complies with the Hicksian principle of induced innovations: technical change *tends to be directed* towards those factors that become expensive, in order to compensate relative scarcity with increased real productivity. As a consequence, balanced growth requires that $\dot{M}/M$ converges to the growth rate of resource price, which is in turn equal to the interest rate.

Two final remarks are as follows. Firstly, the uniqueness and the local stability of the BGP equilibrium hinge on the assumption of poor substitution possibilities: setting $\sigma > 1$ leaves room for multiple long-run equilibria, and in particular, the possibility that the economy shifts towards alternative paths along which the net rate of capital-augmenting technical progress is positive (for details, see Acemoglu 2003a). However, in the present context, our assumption $\sigma < 1$ relies on a precise economic reasoning: natural resource scarcity matters for sustainability to the extent that exhaustible resources are essential for production. Secondly, the necessary condition for non-declining consumption in the long run can be expressed as

$$\left(\frac{1-\beta}{\beta}\right) b^R \left(S_*^R\right) \phi \left(S_*^R\right) \geq \rho + \delta, \tag{3.56}$$

which is obtained by imposing $(\dot{C}/C)_\infty = (\dot{M}/M)_\infty - \rho \geq 0$ in the BGP equilibrium. From (3.56), lower monopoly profits for intermediate firms, as well as higher depreciation rates for innovations, reduce prospects for sustained consumption in the long run.

3.3 Conclusion

The vast majority of capital-resource models assumes that technical progress is, explicitly or implicitly, resource-augmenting. This assumption is necessary to obtain sustained consumption in the long run, but it has not been microfounded so far. At least in principle, R&D activity can also be directed towards capital-augmenting innovations, leaving room for the possibility that technical change does not exhibit resource-saving properties: in this case, most capital-resource models would be too optimistic with respect to the problem of sustainability, and specifying resource-augmenting progress would be a convenient, but strong assumption.

Elaborating on Acemoglu (2003a), we addressed the problem in the context of a multi-sector economy with directed technical change, where the respective rates of capital- and resource-augmenting progress are determined endogenously by the relative profitability of factor-specific innovations. We characterized the balanced growth path, showing that the rate of capital-augmenting technical progress tends to zero in the long run, and the economy exhibits purely resource-augmenting progress. This result provides sound microfoundations for the broad class of capital-resource models in both the Solow-Ramsey and the ETC framework, and contradicts the view that such models are conceptually biased in favor sustainability.

We have shown that the net rate of resource-saving progress must equal the interest rate along the balanced growth path. While this confirms a standard result of the neoclassical model, the presence of directed technical change provides a different, and very intuitive explanation for this result. On the one hand, since the natural resource stock is exhaustible, the growth rate of the resource price is exactly equal to the interest rate Hotelling (1931). On the other hand, balanced growth requires that the rate of resource-saving progress exactly offset the growth in the resource price: this is in compliance with the view that factor-specific innovations are induced by the need of enhancing the real productivity of scarce resources, in order to compensate for their increased expensiveness Hicks (1932). Actually, we do not know whether Hicks and Hotelling had been close friends. But making them meet seventy-five years later was a great pleasure for us.

APPENDIX

C

ADDITIONAL PROOFS AND DERIVATIONS

C.1 Proof of expressions (3.43) and (3.44)

Results (3.43) and (3.44) hold true in a Capital-Labor economy as well, so that the proof is identical to that of Lemma 1 in the Appendix of Acemoglu (2003a, p.28-29). We make use of the index of relative profitability $\Delta(t)$ defined in (3.7), and follow a simple logic: when $x_\infty = 0$, the relative profitability of capital-augmenting innovations grows unboundedly ($\Delta_\infty = \infty$) shifting all scientists into that R&D subsector; symmetrically, $x_\infty = \infty$ implies $\Delta_\infty = 0$, and all scientists will be employed in developing resource-augmenting innovations.

Using (3.24),(3.25),(3.7), (3.37) and equilibrium conditions of instantaneous profits we have

$$\Delta(t) = \frac{\gamma}{1-\gamma} \int_t^\infty x(v)^{\frac{\sigma-1}{\sigma}}\, dv. \tag{C.1}$$

Being $\sigma < 1$, if $x_\infty = 0$ then $\Delta_\infty = \infty$. From (3.7) and (3.27), this will imply $S^K_\infty = S$ and $S^R_\infty = 0$, from which $(\dot{n}/n)_\infty = b^K S\phi(S) - \delta$ and $(\dot{m}/m)_\infty = -\delta$ as in expression (3.43). Conversely, if $x_\infty = \infty$ then $\Delta_\infty = 0$. From (3.27) it follows $S^K_\infty = 0$ and $S^R_\infty = S$, and hence $(\dot{n}/n)_\infty = -\delta$ and $(\dot{m}/m)_\infty = b^R S\phi(S) - \delta$ in expression (3.44).

C.2 Ruling out explosive paths

On the basis of (3.46), we can exclude the possibility of non-balanced growth paths. Unbounded consumption growth can be ruled out as follows: suppose that $(\dot{C}/C)_\infty = \infty$, which in turn requires $(\dot{Y}/Y)_\infty = \infty$. Then, rewrite (3.33) as

$$Y(t) = M(t)\, R(t) \left[\gamma x(t)^{\frac{\sigma-1}{\sigma}} + (1-\gamma) \right]^{\frac{\sigma}{\sigma-1}}. \tag{C.2}$$

Expression (C.2) has the following implications. If $x_\infty = \infty$ then $(x^{\frac{\sigma-1}{\sigma}})_\infty = 0$, which implies $(\dot{Y}/Y)_\infty = (\dot{M}/M)_\infty + (\dot{R}/R)_\infty < \infty$. Also if $x_\infty = \bar{x}$, where $\bar{x}$ is a finite constant, then $(\dot{Y}/Y)_\infty = (\dot{M}/M)_\infty + (\dot{R}/R)_\infty < \infty$. Finally, if $x_\infty = 0$ we have $(\dot{Y}/Y)_\infty < (\dot{M}/M)_\infty + (\dot{R}/R)_\infty < \infty$. Consequently, $(\dot{Y}/Y)_\infty = \infty$ cannot be an equilibrium, implying that $(\dot{C}/C)_\infty = \infty$ cannot be an equilibrium as well.

C.3 Local stability of the BGP equilibrium

The dynamics of the system are represented by five differential equations representing the dynamics of x, N, S^K, $c \equiv C/K$, and $u \equiv H/R$.

We get the first one, describing the evolution of x over time, substituting (3.12) for $\dot{M}/M = (1-\beta)\,\beta^{-1}(\dot{m}/m)$ in (3.40) to obtain

$$\frac{\dot{x}}{x} = \sigma \frac{f(x)}{f'_x(x)\, x} \left[f'_x(x)\, \beta N - \frac{1-\beta}{\beta} \left(b^R \left(S - S^K \right) \phi \left(S - S^K \right) - \delta \right) \right]. \tag{C.3}$$

Differentiating the right hand side of (C.3) with respect to x we have

$$\sigma \left[f'_x(x)\, \beta N - \left(1 - \frac{f''_{xx}(x)}{f'_x(x)} \right) (\dot{M}/M) \right]. \tag{C.4}$$

Evaluating (C.4) at the steady-state equilibrium (where $f'_x(x)\, \beta N = \dot{M}/M$ from (3.40)) we obtain

$$a_{xx} = \sigma \frac{1-\beta}{\beta} \left[b^R \left(S - S^K_* \right) \phi \left(S - S^K_* \right) - \delta \right] f(x_*)\, f''_{xx}(x_*), \tag{C.5}$$

where $f''_{xx} < 0$ implies $a_{xx} < 0$. Differentiating (C.3) with respect to N we have

$$a_{xN} = \sigma \beta f(x_*) > 0, \tag{C.6}$$

and with respect to S we have

$$a_{xS} = -\sigma \frac{f(x_*)}{f'_x(x_*)} \cdot \left[\partial \left(\dot{M}/M \right) / \partial \left(S^K \right) \right] \Big|_{S^K = S^K_*} > 0, \tag{C.7}$$

where the sign comes from $\partial\left(\dot{M}/M\left(S-S^K\right)\right)/\partial S^K<0$. Differentiating with respect to c and u, we get $a_{xc}=a_{xu}=0$.

The equation for the evolution over time of N follows from (3.11):

$$\frac{\dot{N}}{N}=\frac{1-\beta}{\beta}\left(b^K S^K \phi\left(S^K\right)-\delta\right), \tag{C.8}$$

which implies $a_{Nx}=a_{NN}=0$ and, by differentiation with respect to S^K,

$$a_{NS}=\frac{1-\beta}{\beta}b^K\frac{\partial S^K\phi\left(S^K\right)}{\partial S^K}\bigg|_{S^K=S^K_*}>0. \tag{C.9}$$

Again, we obtain $a_{Nc}=a_{Nu}=0$.

The third equation is obtained as in Acemoglu (2003a, p.32). Since $S^K_*>0$ and $S^R_*>0$, the equilibrium condition (3.28) holds in an open set around the BGP equilibrium where both types of innovations are developed. Differentiating (3.28) and substituting (3.11)-(3.12) we have

$$\frac{\dot{S}^K}{S^K}=-\frac{1}{B_1\left(S^K\right)}\left[B_2\left(S^K\right)+B_3\left(S^K\right)\cdot B_4\left(x\right)\right], \tag{C.10}$$

where

$$\begin{aligned}
B_1\left(S^K\right) &= S^K\left(\frac{\phi'\left(S^K\right)}{\phi\left(S^K\right)}+\frac{\phi'\left(S-S^K\right)}{\phi\left(S-S^K\right)}\right), && \text{(C.11)}\\
B_2\left(S^K\right) &= \phi\left(S^K\right)S^K-\phi\left(S-S^K\right)\left(S-S^K\right), && \text{(C.12)}\\
B_3\left(S^K\right) &= \frac{(1-\beta)\,\phi\left(S^K\right)}{\beta\phi\left(S-S^K\right)\left[\rho+\delta+\beta\left(r_*-\rho\right)(1-\beta)^{-1}\right]}, && \text{(C.13)}\\
B_4\left(x\right) &= \xi\left(x_*\right)-\xi\left(x\right), && \text{(C.14)}
\end{aligned}$$

where the capital share $\xi\left(x\right)$ is defined in (3.37) and exhibits $\partial\xi/\partial x<0$. Differentiating (C.10) with respect to S^K and x we have

$$\frac{\dot{S}^K}{S^K}\simeq a_{Sx}\left(x-x_*\right)+a_{SS}\left(S^K-S^K_*\right) \tag{C.15}$$

where little algebra shows that $a_{Sx}>0$ and $a_{SS}>0$. Once more, $a_{Sc}=a_{Su}=0$.

The fourth equation illustrates the dynamic behaviour of the consumption to capital ratio: $c\equiv C/K$. Using the Keynes-Ramsey rule in (3.29), and expressions (3.33) and (3.42), we get:

$$\frac{\dot{c}}{c}=\beta\gamma N f_x'(x)-\rho-N\left[\gamma+(1-\gamma)x^{\frac{1-\sigma}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}+c.$$

The partial derivatives of this expression with respect to the other relevant variables, evaluated at the steady state, are:

$$\begin{aligned}
a_{cx} &= \beta N_* f''_{xx}(x_*) - (1-\gamma) N_* \left[\gamma + (1-\gamma) x_*^{\frac{1-\sigma}{\sigma}} \right]^{\frac{1}{\sigma-1}} x_*^{\frac{1}{\sigma}}; \\
a_{cN} &= \beta \gamma f'_x(x_*) + \left[\gamma + (1-\gamma) x_*^{\frac{1-\sigma}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}; \\
a_{cS} &= 0; \qquad a_{cc} = 1; \qquad a_{cu} = 0.
\end{aligned}$$

Finally, the fifth differential equation we consider concerns the dynamics of the variable $u \equiv R/H$. Using the fact that $\hat{u} = \hat{R} + u$, and the definition of x from (3.34), we get:

$$\begin{aligned}
\hat{u} = \sigma \frac{f(x)}{f'_x(x)\, x} \left[f'_x(x) \beta N - \frac{1-\beta}{\beta} \left(b^R \left(S - S^K \right) \phi \left(S - S^K \right) - \delta \right) \right] + \frac{1-\beta}{\beta} b^R \left(S - S^K \right) \\
\phi \left(S - S^K \right) - \frac{1-\beta}{\beta} b^K S^K \phi \left(S^K \right) - N \left[\gamma + (1-\gamma) x^{\frac{1-\sigma}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} + c + u.
\end{aligned}$$

The coefficients of the linear approximation are:

$$\begin{aligned}
a_{ux} &= a_{xx} - (1-\gamma) N_* \left[\gamma + (1-\gamma) x_*^{\frac{1-\sigma}{\sigma}} \right]^{\frac{1}{\sigma-1}} x_*^{\frac{1}{\sigma}}; \\
a_{uN} &= a_{xN} + \left[\gamma + (1-\gamma) x_*^{\frac{1-\sigma}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}; \\
a_{uS} &= a_{xS} - \left(1 + \frac{b^R}{b^K} \right) a_{NS}; \qquad a_{uc} = 1; \qquad a_{uu} = 1.
\end{aligned}$$

$$\begin{pmatrix} \dot{x}/x \\ \dot{N}/N \\ \dot{S}^K/S^K \\ \dot{c}/c \\ \dot{u}/u \end{pmatrix} \simeq \begin{pmatrix} a_{xx} & a_{xN} & a_{xS} & 0 & 0 \\ 0 & 0 & a_{NS} & 0 & 0 \\ a_{Sx} & 0 & a_{SS} & 0 & 0 \\ a_{cx} & a_{cN} & 0 & a_{cc} & 0 \\ a_{ux} & a_{uN} & a_{uS} & a_{uc} & a_{uu} \end{pmatrix} \times \begin{pmatrix} x - x_* \\ N - N_* \\ S^K - S^K_* \\ c - c^* \\ u - u^* \end{pmatrix}. \tag{C.16}$$

The determinant of the coefficients matrix, **J** say, can be written as:

$$|\mathbf{J}| = a_{uu} a_{cc} |\mathbf{A}|,$$

where we let

$$\mathbf{A} \equiv \begin{pmatrix} a_{xx} & a_{xN} & a_{xS} \\ 0 & 0 & a_{NS} \\ a_{Sx} & 0 & a_{SS} \end{pmatrix}.$$

Hence, $a_{uu} > 0$ and $a_{cc} > 0$ are two positive eigenvalues of **J**. Studying the determinant and the characteristic equation of **A** provides the three additional eigenvalues of the system. Since the determinant of $\mathbf{A}$ is $a_{xN}a_{NS}a_{Sx} > 0$, we have either three positive roots, or one positive and two negative (or complex with negative real part) roots. The three remaining eigenvalues (λ_i) are also zeros of

$$P(\lambda) = -\lambda^3 + \lambda^2 (a_{xx} + a_{SS}) + \lambda (a_{Sx}a_{xS} - a_{xx}a_{SS}) + a_{Sx}a_{NS}a_{xN} = 0,$$

where $(a_{Sx}a_{xS} - a_{xx}a_{SS}) > 0$ and $a_{Sx}a_{NS}a_{xN} > 0$. Hence, regardless of the sign of $(a_{xx} + a_{SS})$, the polynomial always shows one variation of signs (either -,+,+,+ or -,-,+,+). This implies the existence of one and only one positive root.

Our analysis thus shows that the system in (C.16) has three positive and two negative roots. Indeed, two initial conditions $N_0 = N(0)$ and $x_0 = \frac{N_0 K_0}{M_0 R_0}$ are needed to converge to the long-run equilibrium. Notice that u_0 is univocally determined by x_0, according to $u_0 = \frac{N_0 K_0}{M_0 H_0 x_0}$, and is thus not an independent jump variable. To conclude, the number of negative eigenvalues equals the number of necessary initial conditions and the system is locally stable.

CHAPTER FOUR

BRAIN DRAIN AND DISTANCE TO FRONTIER[1]

Classical theoretical studies on the *Brain Drain* hold that emigration of highly educated people is beneficial for destination countries and harmful for source ones (e.g. Borjas 1994, Borjas 1995). For immigration countries, the inflow of highly skilled individuals increases the pool of available human capital, and boosts economic growth in the long-run. A specular logic seems to imply that the outflow of 'brains' is damaging for the source countries.[2]

This theoretical prediction, however, is at odds with the experience of some sending countries that grew faster than their relatively more closed neighbours. Examples include Japan, South Korea, Taiwan and Singapore as opposed to Bangladesh, India and Indonesia, for example.[3] A recent literature on the effects of the outflow of skilled workers has focused on the potential for a *Beneficial Brain Drain* (BBD), or a *Brain Gain*. The central proposition of studies such as Mountford (1997), Stark, Helmenstein, and Prskawetz (1997) and (1998), Vidal (1998), and Beine, Docquier, and Rapoport (2001) is that, if the possibility of emigration induces more skill-creation than skill-loss, source

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[1] This chapter builds on Di Maria and Stryszowski (2006).

[2] Several theoretical studies have pointed at the potential negative effect of the outflow of human capital on source countries, among others: Bhagwati and Hamada (1974), Kwok and Leland (1982), Galor and Tsiddon (1997a), and Miyagiwa (1991).

[3] Japan and, to a greater extent, South Korea experienced high levels of skilled emigration in the past decades. South Korea, for example, still had a rate of brain drain of over 9% among highly skilled workers in 1990. In the same year Taiwan and Singapore exhibited even higher rates: 15.2% and 24.8%, respectively. By comparison India (3.9%), Bangladesh (2.1%), and Indonesia (3.9%) suffered a much smaller drain of human capital. This high rates of brain drain notwithstanding, Japan and the Asian Tigers where much more successful in terms of economic performance than the countries in the other group.

countries might actually increase their stock of human capital, as the possibilities of moving and working abroad increase. One of the simplest mechanisms behind results of this type is that the possibility of emigration might lead economic agents to invest more in their human capital. Yet, since not all of them emigrate in the end, also those who stay in the country of origin have a higher human capital than would otherwise have been the case. Under such circumstances, the simple ‘drain’ effects emphasized by earlier contributions are (possibly) more than compensated by these ‘gain’ effects.

Empirical investigations of the effects of skilled migration on source countries have provided mixed results. While most authors would agree that migration of skilled workers is positive for the destination country,[4] there is no consensus as refers to the effects on the source economies. Recent empirical work by Beine, Docquier, and Rapoport (2003) has indeed shown that the net effect of the brain drain can be either positive or negative. Despite the significant and positive effect on human capital accumulation that they are able to identify, Beine, Docquier, and Rapoport show that the effects in terms of annual GDP growth are more mixed. Indeed, according to their estimates the BBD hypothesis is supported by the data only for a small number of countries. The authors conclude by noting that "*the simple fact that, among sending countries there are winners and losers, points to the necessity of a better understanding of the circumstances and factors favouring the occurrence of a detrimental brain drain*".[5] In this chapter we aim at contributing to the debate on the brain drain by focussing on the role played by the *composition* of human capital in fostering productivity growth and, finally, economic development.

The BBD hypothesis implicitly assumes that the human capital that is accumulated with a view to emigration can prove useful once people remain in their country of origin. One might ask if this is a realistic assumption. Indeed, it runs counter to some empirical evidence showing that countries with similar *levels* but different compositions of education (which we use as a proxy for human capital accumulation) by type have very different performances in terms of convergence and growth. If all human capital would be useful, a higher level thereof would imply faster GDP growth, irrespective of its composition, all else equal.

Although not much addressed in the literature, the different roles played by different types of human capital at different stages of development has been recognized by a number of authors. Both Durlauf and Johnson (1997) and

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[4] An excellent reference on these issues is Borjas (1990).

[5] Beine, Docquier, and Rapoport (2003), p.35.

Krueger and Lindahl (2001) provide evidence as to the heterogenous effects of education on growth across countries with different levels of development. Kalaitzidakis, Mamuneas, Savvides, and Stengos (2001), instead, discuss the existence of non-linearities in the education-growth relationship.

Based on this, in what follows we claim that not all the human capital accumulated in view of possible emigration is *appropriate* for the technology available in the source country, and for its level of development. In particular, we postulate that the distance to the technological frontier is a key determinant for understanding the effects of human capital accumulation/composition on economic growth. While the accumulation of human capital seems to imply faster technological advancement and economic growth, we point at the different *types* of human capital that are most useful at different stages of development. This view reflects the idea that technological advances become available either through imitation or through innovation, and that each activity requires (a different combination) of different types of skills. It is reasonable to assume that imitation requires a more technically inclined work force, whereas the more complex activity of innovation requires more than technical skills alone. Indeed, the closer economies are to the frontier, the more complex their economic and institutional systems, the higher their need for a balanced work force comprising technical skills, creativity, humanistic competencies, legal and managerial expertise. Conversely, at earlier stages of economic development, when the main task is to copy and adapt available technologies, a more intense specialization in technical skills can prove helpful in catching up.

Following Vandenbussche, Aghion, and Meghir (2006), we model two economies that can be parameterized by their distance from the technological frontier. Economic development is driven by productivity growth, and productivity improvements depend on the amount and the composition of the human capital available in the country, besides on the distance from the technological frontier. Once at the frontier of technology, productivity advances are only possible through innovation, whereas imitation occurs further away from the frontier. Following on our argument above, we assume that imitation is more intensive in technical skills than innovation.

To investigate the distortionary effects of migration on the accumulation of human capital, we model human capital accumulation by agents as an endogenous decision. By letting the type of skills acquired be determined by the costs and benefits faced by heterogenous agents, we add one important dimension to our model. We are in fact able to investigate the interaction between labour market outcomes, migration possibilities and institutional arrangements, such as the existence of educational policies targeted at satisfying the needs of the local economy.

Our results show that the possibility of migration distorts the incentives for agents to accumulate the type of human capital that is appropriate for the country of origin, given its level of development. We show that when migration becomes possible at early stages of economic development the growth rate of the source economy decreases. We discuss circumstances under which this process leads to development traps, i.e. situations where the process of convergence to the technological frontier stops prematurely. Furthermore, we show that educational policies, in the form of subsidies to particular types of skills, can counteract the negative effects of migration on growth. Assuming that in democratic societies migration cannot be (completely) prevented, our analysis delivers a clear policy recommendation: Countries that wish to maximize their convergence potential should take this mechanism into account and increasingly subsidize appropriate skills, the further away they are from the technological frontier, and the easier the prospects of migration.

4.1 Education, migration and economic development

At the aggregate level, the relationship between brain drain and economic growth is far from univocal. To illustrate this point, we consider the growth rates of the GDP for 128 countries in 2000 and their rate of brain drain – measured as the percentage of tertiary educated residents who emigrate – ten years earlier. Figure 4.1 presents the scatter plot of the two variables and the regression line. The two variables show very little evidence of being correlated, in fact the correlation coefficient, ρ, equals 0.06.[6]

The lack of any significance of this aggregate relationship does not mean much, however, as it simply hides a whole range of situations where countries experienced different degrees of brain drain and various degrees of success in terms of economic growth. Among these, we find the experience of the East Asian economies to be one of the most interesting.

In the last fifty years countries like Japan, the Republic of Korea, Singapore, Hong Kong and Taiwan all exhibited astonishing growth rates. At the

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[6] The regression equation is: $\%\Delta \mathit{GDP2000} = \underset{(0.42)}{2.35} + \underset{(1.46)}{0.91} \cdot \%\mathit{BrainDrain1990}$. The GDP growth rates are derived from the Penn World Table 6.1 from Heston, Summers, and Aten (2002), the rates of brain drain from Docquier, Lohest, and Marfouk (2005).

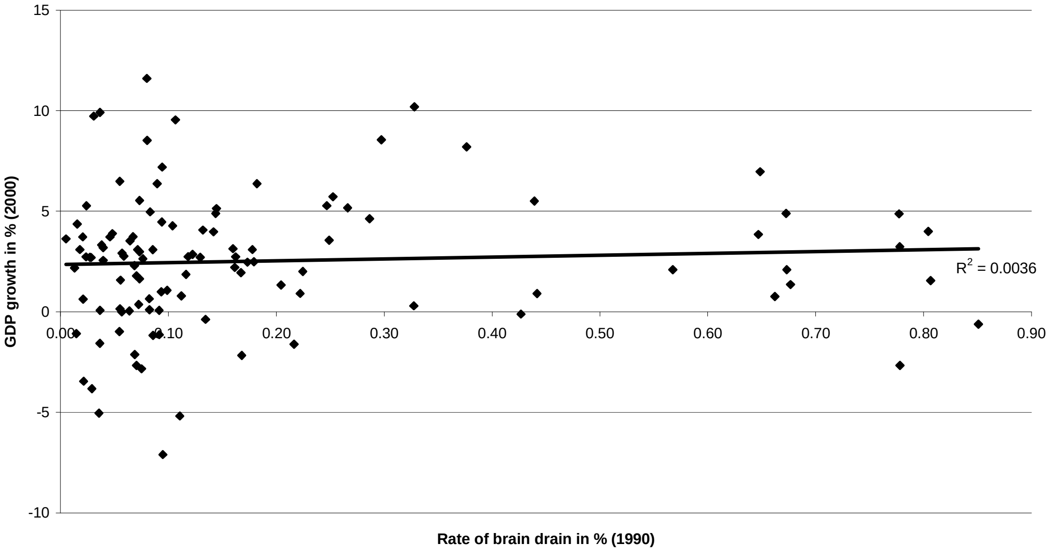

Figure 4.1: *GDP growth and brain drain.*

Source: Penn World Table 6.1 and Docquier, Lohest, and Marfouk (2005).

same time, they pursued a policy of open borders, i.e. a significant share of their highly skilled workers left over the years to work abroad. Compared to countries with similar rates of brain drain and initial levels of development, however, these East Asian economies performed much better and managed to catch-up with first-world standards of living (and technological knowledge) within a short time period.

There are many important lessons to be learned from the experience of these countries and, indeed, many pages have been filled with analyses of the East Asian "miracle".[7] Here we draw attention to one specific aspect of these economies that has not been fully appreciated by previous analyses: all these economies have exhibited a marked commitment of the government to promote the accumulation of particular types of skills. As World Bank (1993) puts it, "*public funding of post-secondary education focused on technical skills* [...] *The result of these policies has been a broad,* technically inclined *human capital base well-suited to rapid economic development*".[8]

Despite having shares of public expenditure on education in line with, and

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[7] Two important references analyzing, and rethinking, the East Asian economies' impressive performance are World Bank (1993) and (2001).

[8] Ibid., page 15. Emphasis added.

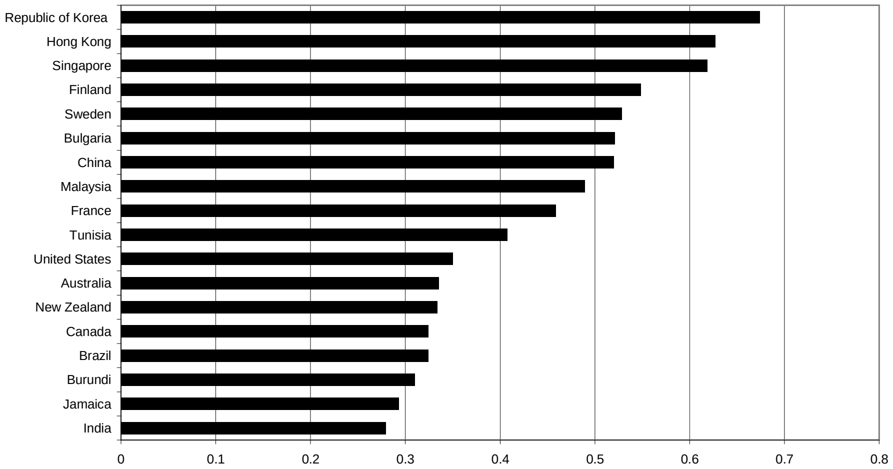

Figure 4.2: *Share of science and engineering students on total tertiary education (1980).*

Source: Own calculations on United Nations Common Data-Base (UNCDB) data.

sometimes lower than those in other developing countries,[9] the East Asian economies chose to support the accumulation of specific types of skills which were deemed most useful to economic development. As shown by the graph in Figure 4.2, there is no clear relationship between the accumulation of 'technical' skills and the level of economic development. The Figure reports the percentage of science and engineering students in the total, in 1980, for an indicative cross-section of developed and developing countries.[10] One remarkable feature of these data is that both poor and rich countries exhibit either high or low shares of technical students (China vs. India or Finland and Sweden vs. New Zealand and Canada, for example), so that no clear pattern is visible. What is apparent, instead, is that countries like the Republic of Korea, Hong Kong and Singapore are at the top of the distribution.

Can this high share of technically skilled workers explain, at least in part, the success of the East Asian economies? Another simple graph lends support to this claim. Figure 4.3 plots the growth rate of a number of developed and developing countries in 1990, against the share of science and engineering

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[9] In 1960, for example, the Republic of Korea spent 2.0% of its GDP on education, in the same year Brazil's share was 1.9%, and the average for Sub-Saharan African countries was 2.4%. In 1989, Korea's budget for education increased to 3.6%, Brazil's reached 3.7% and for the same sub-set of African countries the share topped 4.1%. These figures are taken from World Bank (1993), table 5.3.

[10] Figure 4.2 is based on computations by the authors on UNCDB data.

students on total tertiary education in 1980 and the corresponding regression line.[11] The plot seems to imply that having a higher share of science and technology students is an advantage in terms of growth performance.

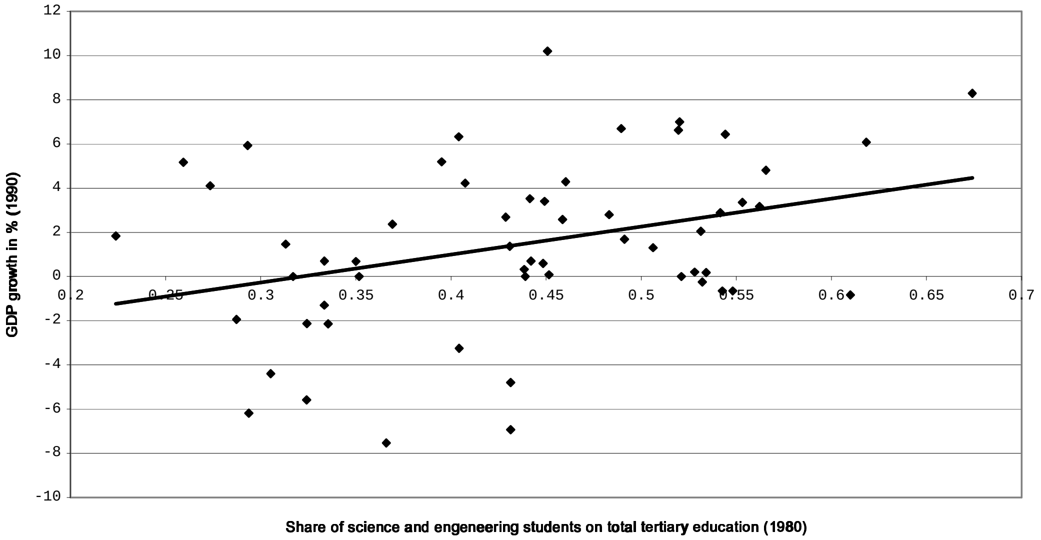

Figure 4.3: *GDP growth (1990) and the share of S&E students (1980).*

Source: Penn World Table 6.1 and UNCDB.

The other interesting aspect is how such a composition of human capital was obtained. Most East Asian economies, in fact, represent clear examples of the government's intervention into the structure of the tertiary education. In Japan, for example, the system comprising the National Institute for Educational Policy Research (NIER), founded in 1949, and the Ministry of Education, Sports and Culture,[12] has for a long time been perceived as the "Superministry" responsible for adjusting the structure of Japanese schooling to the needs of local industries. Similar institutional structures also exist in the countries of the group of the so-called "Asian Tigers".

More recently, however, there has been an increasing effort to move away from the predominance of the government and towards the utilization of market mechanisms, especially in Japan where a deep reform of the educational system is currently under way. Analysts have argued that such moves reflect

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[11] The equation representing the line is: $\%\Delta GDP1990 = -\underset{(-1.82)}{4.13} + \underset{(2.58)}{10.97} \cdot \%S\&E1980$; the sample consists of 53 countries. Data derived from the Penn World Table 6.1 and the UNCDB.

[12] In January 2001, the former Ministry of Education, Sports and Culture and the former Science and Technology Agency were merged and the new Ministry of Education, Culture, Sports, Science and Technology was founded.

fundamental shifts in the mode and direction of social development. To quote a recent OECD report *"the increased diversity and complexity of the modern society and its needs, necessarily have made centralized decision and control obsolete* [...] [*M*]*arket mechanisms will be the only way to achieve diversified and multidimensional changes*".[13]

This shift in paradigm is consistent with the main ideas of our proposed framework. Since the advancement of knowledge, which is at the basis of economic growth, can either occur through the creation of new technologies (ideas) or through the adoption of old technologies from abroad, and since the two activities require different compositions of human capital, the optimal structure of human capital depends crucially on the stage of development of any given economy. Thus, in the presence of distortions, different types of public policies can be necessary to favour the accumulation of different types of human capital at different stage of development.

We focus on the possibility of migration as one such potential distortion. By blurring the borders between economic systems at different levels of economic development, migration distorts the incentives for the optimal accumulation of human capital: agents in lagging countries prefer to acquire the type of human capital that would be more profitable in case of successful migration. Thus the distance to frontier in different countries could offer a useful key to understand the effects of the brain drain on economies at different stages of development.

Moreover, policy could provide a way to offset this harmful effect of brain drain on human capital composition, by regulating the structure of education, as we will argue in what follows.

4.2 The model

We describe an economy consisting of two countries, one large destination country and one small source one. We assume that the destination country (which we can think of as the group of the OECD countries for concreteness) is the technological leader, whereas the source country is technologically less developed.[14]

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[13] This quote is from the Japanese National Report of the OECD IMHE-HEFCE project on international comparative higher education financial management and governance, 2004.

[14] In what follows, we use the terms *destination country*, *technological leader*, and *leading country* interchangeably. The same applies to the terms *source country*, *technological follower*, and

The economies are populated by workers and firms. Workers accumulate skills, and supply skilled labour to firms. Skill accumulation is costly in that some time is necessary to acquire knowledge. We assume that workers differ in their abilities (their 'talent'), so that certain types of skills are more difficult to accumulate (i.e. more time is required) for some agents than for others. For simplicity, we assume that all workers accumulate skills and that it is only possible to acquire two types of skills which we broadly label 'technical' and 'general'. Consequently, in the model there are two types of workers: technically-skilled (T) and generally-skilled (G) ones.

Since the net rewards to the accumulation of different skills depends on the wage commanded by the specific skill and the cost it entails (in terms of foregone earnings), each worker decides on the type of skills she wants to acquire based on her specific type.

Each firm engages in production of an intermediate, needed in the production of the final good, and invests in technology improvements. We assume that workers are only used in the latter activity. Hence, firms decide how many workers of each type to employ in the 'research' sector, given that technology can be improved either through R&D activities (innovation proper), or by adopting existing technologies from the world technological frontier (imitation).

In the next subsections we describe in greater details the accumulation decisions made by workers and the parallel innovation choices facing firms. We discuss the choices in a situation of autarchy, that is a situation in which no migration possibility exists. This discussion fully characterizes the destination country, given our assumption that it is large enough that smaller foreign markets are not relevant to its agents' decisions. Notice, moreover, that throughout the chapter we ignore the possibility that goods be traded; we do this to be able to clearly identify the effect of migration on workers' accumulation decisions. Hence, the alternative to autarchy in our framework is simply a situation in which workers are allowed (with some positive probability) to move from the lagging to the leading country.

4.2.1 Investment in education

Each period new cohorts of workers of fixed size are born in each country, thus there is no population growth. We assume that the population size in the

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lagging country.

leading country, $\bar{L}$, is larger than L, the population in the lagging country. We further assume that the share of entrepreneurs in the population is the same in both economies. This has two consequences: first, the number of firms is larger in the leading rather than in the lagging country; second, the number of workers per firm will be the same across countries. In this fashion, the relative size of the two economies plays no role in the model. Without loss of generality, as long as we only look at one country at the time, we can simplify the analysis by letting the population size equal 1.

Workers only live for one period: each period new agents are born, they decide about their education, they work for a wage, consume all their income and finally die.

Workers are risk neutral and differ only with respect to the cost they have to incur to accumulate different types of human capital. They are indexed by j according to their talent and uniformly distributed over the interval $[0, 1]$, with the convention that $j = 1$ corresponds to the most talented individual. The talent of an agent determines her relative cost of acquiring general skills. Agent j needs to spend a fraction $1 - j$ of her time to acquire these skills, while we assume that the time-cost of acquiring technical skills is independent of talent and equal to $1 - \xi$ for all workers, where $\xi \in (0, 1)$.[15] Agent j will thus be able to offer j units of general skills, or ξ of technical skills. Our modelling choices don't make general skills overly costly for any individual, however, for some of them technical skills are easier to acquire and they will therefore invest in that direction.

The composition of skills between technical and general ones will be determined by the relative costs of skills accumulation, and by the relative rewards to the particular kind of skills. Letting the salary for a G-skilled worker at time t be $w_{Gt} = \omega_{Gt}\, A_{t-1}$ – where ω_{Gt} is the wage per effective unit of human capital provided at time t, and A_{t-1} indicates the level of total factor productivity at time $t - 1$ – and the salary for a T-skilled individual be $w_{Tt} = \omega_{Tt}\, A_{t-1}$, it is possible to identify the marginal worker, j'. Agent j', the worker who is indifferent between acquiring technical skills (and earning w_T per each unit she provides) and general ones (thereby earning w_G per unit), must satisfy the following condition:

$$\omega_{Tt}\, \xi = \omega_{Gt}\, j'. \tag{4.1}$$

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[15] Effectively this only means that, using the difficulty of developing technical skills as a benchmark, general skills are relatively easier to acquire for some individuals, and more difficult for others.

All agents indexed by $j \in [0, j']$, will accumulate technical skills, conversely, agents with $j \in (j', 1]$ will choose to become generalists.

Accordingly, the total supply of G-skilled labour equals,[16]

$$G_t = \int_{j'}^{1} j \, \mathrm{d}j = \frac{1}{2}\left(1 - j'^2\right);$$

which can be easily solved for j', yielding:

$$j' = \sqrt{1 - 2\,G_t}. \tag{4.2}$$

Rearranging equation (4.1) and using the above expression to substitute for j', we get the following expression for the supply of G-skilled labour:

$$\omega \equiv \frac{\omega_{Gt}}{\omega_{Tt}} = \frac{\xi}{\sqrt{1 - 2\,G_t}}. \tag{4.3}$$

Finally, note that the constraint that $j \in [0, 1]$ implies that the supply of graduates with technical background depends on the supply of G-skills. Hence, the supply of T-skilled labour is given by:

$$T_t = \xi j' = \xi \sqrt{1 - 2\,G_t}. \tag{4.4}$$

4.2.2 Production and technological progress

In the leading country there are $\bar{N}$ firms, while in the lagging country there are only $N < \bar{N}$ of them. As discussed above, the number of firms in each country is proportional to the number of workers in each country, so that the size of the economy is immaterial. Thus, for the sake of generality, we indicate the number of firms by ν in what follows. Each firm produces one intermediate input for the production of final output, and engages in productivity-enhancing activities employing skilled workers.

Final output is produced competitively using a continuum of mass ν of intermediates, accordingly to the following production function:

$$Y_t = \int_0^{\nu} A_t^{1-\alpha} x_{i,t}^{\alpha} \mathrm{d}i, \tag{4.5}$$

where $\alpha \in (0, 1)$ and $x_{i,t}$ is the amount of intermediate good i used to produce Y at time t .

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[16] Notice that this specification implies $G \leq 1/2$.

Each intermediate producer acts as a (local) monopolist and produces good i using the final good with a one-to-one technology. It is then easy to show that, for a given level of A_t, the equilibrium demand for input i equals $x_{i,t} = \alpha^{\frac{2}{1-\alpha}} A_t$. Hence, profit maximization on the part of intermediate goods' producers implies that for each firm monopoly profits equal:

$$\pi_t = \zeta A_t, \tag{4.6}$$

where $\zeta \equiv \frac{1-\alpha}{\alpha} \alpha^{\frac{2}{1-\alpha}}$.

Thus, firms maximize their profits by maximizing their productivity level. Moreover, using the expression for inputs' demand derived above, it is straightforward that the level of final output is linear in the level of technology and, as a consequence, the growth rate of output will be the same as the growth rate of technology. Keeping this in mind, we now analyze the choice faced by firms in formulating their technological development plans.

Firms employ skilled workers to increase productivity. We assume that productivity can be improved by directly involving in R&D activity or by adopting existing technologies from the world technological frontier:[17]

$$A_t = A_{t-1} + A_{t-1} T_{nt}^{\phi} G_{nt}^{1-\phi} + (\bar{A}_{t-1} - A_{t-1}) T_{mt}^{\sigma} G_{mt}^{1-\sigma}. \tag{4.7}$$

Here T_{nt} represents the amount of T-skills used in innovation at time t, while T_{mt} refers to the amount in imitation. The same applies to G_{nt} and G_{mt}. We assume that both types of skills are needed in both innovation and imitation, and that the two activities differ in that the productivity of G-skilled workers is higher in innovation than in imitation, i.e. we let $\sigma > \phi$.

Furthermore, the technological improvement function in (4.7) implies that imitation is more productive the further away a country is from the technological frontier, $\bar{A}$. This is intuitive since a larger technological gap means that more innovations can be usefully adopted from abroad. Innovation, instead, becomes more productive with the own technology level, A, formalizing the idea that a broader technological base is needed to push the frontier further.

4.3 Equilibrium under autarchy

To characterize equilibrium situations under autarchy, we need to discuss three possible types of equilibrium according to the regime of technological

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[17] This modelling choice closely follows Vandenbussche, Aghion, and Meghir (2006), who, in turn, derive it from Benhabib and Spiegel (1994) and Acemoglu, Aghion, and Zilibotti (2006).

change that takes place. In what follows, we distinguish between equilibria that occur under innovation, equilibria that obtain under imitation, and mixed equilibria where both activities take place at the same time.

Let us start with the case where innovation is the only type of productivity-enhancing activity performed in equilibrium. In this case, new technologies develop according to:[18]

$$\bar{A}_t = \bar{A}_{t-1} + \bar{A}_{t-1}\bar{T}_t^{\phi}\bar{G}_t^{1-\phi}. \tag{4.8}$$

Profit-maximizing firms will choose the amount of each type of skilled labour to employ in innovation, in order to solve the following maximization problem:

$$\max_{\bar{G}_t,\bar{T}_t} \pi_t = \zeta\bar{A}_t - \bar{\omega}_{Tt}\bar{A}_{t-1}\bar{T}_t - \bar{\omega}_{Gt}\bar{A}_{t-1}\bar{G}_t, \tag{4.9}$$

subject to (4.8).

The first-order conditions for this problem are,

$$\begin{aligned} \bar{\omega}_{Gt} &\equiv \frac{\bar{w}_{Gt}}{\bar{A}_{t-1}} = (1-\phi)\zeta\left(\frac{\bar{T}_t}{\bar{G}_t}\right)^{\phi}, \text{ and} && (4.10)\\ \bar{\omega}_{Tt} &\equiv \frac{\bar{w}_{Tt}}{\bar{A}_{t-1}} = \phi\zeta\left(\frac{\bar{T}_t}{\bar{G}_t}\right)^{\phi-1}. && (4.11) \end{aligned}$$

The above equations, together with (4.3) constitute the equilibrium. Taking the ratio of (4.10) and (4.11) and substituting for $\bar{T}$ from the expression in (4.4), one gets the following expression for the demand of G-skilled labour:

$$\bar{\omega}_t \equiv \frac{\bar{\omega}_{Gt}}{\bar{\omega}_{Tt}} = \frac{1-\phi}{\phi}\frac{\sqrt{1-2\,\bar{G}_t}}{\bar{G}_t}. \tag{4.12}$$

Using this and the supply function in (4.3), we can illustrate the equilibrium graphically in the (ω, G_t) plane (see Figure 4.4, where $\omega \equiv \bar{\omega}_{Gt}/\bar{\omega}_{Tt}$). The demand for generalists is represented with the downward sloping curve $\bar{D}$, whereas the supply is represented by the upward sloping curve S. The equilibrium obtains when both conditions are satisfied simultaneously, that is at a point like $(\bar{\omega}^*, \bar{G}^*)$. This point represents the equilibrium when a country is fully specializing in innovation, thus this is the equilibrium prevailing the destination country.

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[18] From now on, we identify variables that refer to the innovation-only case by an upper bar. Variables without the upper bar refer the imitation-only equilibrium. When necessary, we will distinguish the mixed equilibrium variables with a tilde: $\sim$.

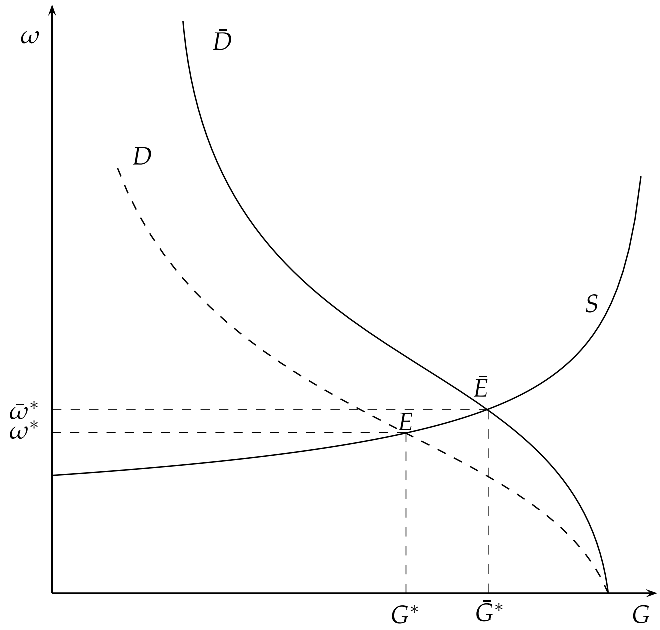

Figure 4.4: *The equilibrium without migration in the two countries.*

Analytically, it is straightforward to solve for the equilibrium level using (4.3) and (4.12), to get:

$$\bar{G}^* = \frac{1}{\xi\Phi + 2}, \text{ and } \bar{\omega}^* = \xi\sqrt{\frac{\xi\Phi + 2}{\xi\Phi}},$$

where we have used $\Phi \equiv \frac{\phi}{1-\phi}$.

At the other extreme, we focus on the case in which a country only resorts to imitation to increase their technological level. Local firms, thus fully specialize in imitation. Except for this, they behave exactly like their counterparts in the previous case: amending the relevant production function, they choose G_t and T_t to maximize their profits,

$$\max_{G_t,T_t} \pi_t = \zeta\left[A_{t-1} + (\bar{A}_{t-1} - A_{t-1})T_t^{\sigma}G_t^{1-\sigma}\right] - \omega_{Tt}A_{t-1}T_t - \omega_{Gt}A_{t-1}G_t. \tag{4.13}$$

Hence, their demand for G-skilled labour equals:

$$\omega_t = \left(\frac{1-\sigma}{\sigma}\right)\frac{\sqrt{1-2G_t}}{G_t}.$$

Since $\sigma > \phi$, the demand curve for the case of imitation (the dashed line D in Figure 4.4) lies below the demand curve for innovation. Intuitively, it is clear that, since skills of type G are more productive in innovation than in imitation, for any given relative wage firms specializing in innovation would demand relatively more G skills than firms specializing in imitation. Just as before, the equality of demand and supply will determine the equilibrium levels of the relative wage and of the supply of G-skills:

$$G^* = \frac{1}{\xi\Sigma + 2}, \text{ and } \omega^* = \xi\sqrt{\frac{\xi\Sigma + 2}{\xi\Sigma}},$$

where $\Sigma \equiv \frac{\sigma}{1-\sigma}$.

From $\sigma > \phi$, we conclude that when countries fully specialize, the country that does so in innovation will have a higher level of G.

To complete our analysis, we need to address what happens when firms don't fully specialize in either activity. In this case, they will adopt the combination of the two activities which allow them to maximize their profits. In terms of Figure 4.4, equilibria of this type will correspond to points along the supply curve S, comprised between E and $\bar{E}$. The weight of each type of activity, innovation and imitation, will be determined by the relative productivity of each. The higher is the weight of imitation, the closer the mixed equilibrium will be to E, and *vice versa* for innovation.

As mentioned at the end of the previous section, the productivity of imitation is higher, the wider the technological gap. Innovation, on the other hand, is more productive the closer a country is to the technological frontier. Thus, at an intuitive level it seems reasonable that, as we move up along the technological ladder, we encounter countries progressively more active in innovation. In terms of Figure 4.4, this implies that the equilibrium would gradually shift from point E, where only imitation occurs, to point $\bar{E}$, where innovation is the only activity taking place.

Given the structure of (4.7), countries that have a low level of technology have larger incentives – represented by the term $(\bar{A}_t - A_t)$ – to engage in imitation. These incentives, however, decrease with the reduction of the distance to frontier. Thus, it would seem that imitation occurs far away from the frontier; imitation and innovation coexist as the distance to frontier gets smaller; while only innovation takes place for low levels of the technological gap. Indeed, in the proposition that follows we show that the choice of the type of activity to undertake only depends on the distance-to-frontier parameter, that we define as $a_t = \bar{A}_t / A_t \geq 1$.

Proposition 4.1. *Consider the economy described above. There exist two critical values of the distance to frontier –* $\widetilde{a}_l$ *and* $\widetilde{a}_h$ *– such that, when* $a_{t-1} < \widetilde{a}_l$*, only* *innovation occurs in the equilibrium; when* $a_{t-1} > \widetilde{a}_h$*, only imitation occurs in the equilibrium; and when* $a_{t-1} \in (\widetilde{a}_l, \widetilde{a}_h)$*, both activities take place in the equilibrium.*

Proof. See Section D.1 in the Appendix for the proof, and for the expressions of $\widetilde{a}_l$ and $\widetilde{a}_h$. □

According to this proposition, there are values of the distance-to-frontier for which both innovation and imitation occur simultaneously: this is indeed the case when a_{t-1} lies between $\widetilde{a}_l$ and $\widetilde{a}_h$, as defined in Section D.1 of the Appendix. In this case, the equilibrium is characterized by a value of the wage that depends on a_{t-1}, $\widetilde{\omega}(a_{t-1})$, defined as

$$\widetilde{\omega}(a_{t-1}) \equiv \left[(a_{t-1} - 1)\frac{1-\sigma}{1-\phi}\left(\frac{\sigma}{1-\sigma}\right)^{\sigma}\left(\frac{1-\phi}{\phi}\right)^{\phi}\right]^{\frac{1}{\phi-\sigma}}, \tag{4.14}$$

and such that $\widetilde{\omega}(a_{t-1}) \in (\omega^*, \bar{\omega}^*)$. The corresponding level of the total supply of skills, $\widetilde{G}(a_{t-1})$ say, can be read on the labour supply curve, S in Figure 4.4.

Hence, our economies have an equilibrium at (ω^*, G^*) for all levels of $a_{t-1} \in [\widetilde{a}_h, +\infty)$, in which case full-specialization in imitation will obtain; the equilibrium switches to a non-specialization regime with both imitation and innovation happening at the same time, and $(\widetilde{\omega}(a_{t-1}), \widetilde{G}(a_{t-1}))$ for intermediate levels of a i.e. for $a_{t-1} \in (\widetilde{a}_l, \widetilde{a}_h)$; finally, full specialization in innovation will occur when $a_{t-1} = \widetilde{a}_l$. In this last case, the wage rate and the equilibrium level of G-skills are $\bar{\omega}^*$ and $\bar{G}^*$, respectively.

Before moving on to considering how the distance to frontier of the lagging country evolves over time, there is another important point to make. Since the labor market is competitive, the wages equal marginal products, hence there are no extra profits from innovation. However the monopoly profits in the market for intermediates depend on the productivity level. In the absence of any external distortions, thus, the technological level is maximized. Since the growth rate of technology is given by $g_t = (A_t - A_{t-1})/A_{t-1}$, and A_{t-1} is predetermined, the maximization of technology improvements results in output growth maximization at each point in time. In other terms, in the absence of any other distortions, the market mechanisms are enough to generate the appropriate incentives for firms and workers to allocate resources optimally (in terms of growth). We close this section with the following result:

Proposition 4.2. *In the absence of migration, the market solution is growth maximizing.*

Proof. See Section D.2 in the Appendix. □

4.4 Convergence under autarchy

Having described the possible equilibria, in this section we analyze the evolution over time of the distance to frontier in the source country when no migration is possible. We show that the lagging country tends to grow faster than the leading one, and converging over time towards the technological frontier. Recall that the distance to frontier at time t is defined as:

$$a_t = \frac{\bar{A}_t}{A_t} \geq 1,$$

thus, as long as the growth rate of the lagging country is larger than the growth rate of the leading one, convergence towards the frontier will occur, that is a_t will decrease over time.

Under autarchy, both the leading and the lagging country enjoy a growth maximizing allocation of workers across skills, that is the ratio T_t/G_t that arises in equilibrium, maximizes the growth rate as shown above in Proposition 4.2.

The growth rate for the leading country, $\bar{g}$, is given, from (4.8), by

$$\bar{g} = \frac{\bar{A}_t - \bar{A}_{t-1}}{\bar{A}_{t-1}} = \bar{T}_t^{\phi} \bar{G}_t^{1-\phi},$$

and it only depends on the equilibrium levels of $\bar{T}_t$ and $\bar{G}_t$, which are independent of a_t and constant over time.

To determine the evolution over time of the distance to frontier of the lagging economy, we need to compare its growth rate with the growth rate of the frontier country, $\bar{g}$. Consider first what happens when the source country is very far from the frontier and, in particular, when its distance to frontier, a_t, is larger than the critical value $\widetilde{a}_h$. Under these circumstances, the lagging country fully specializes in imitation and its growth rate is given by $(a_{t-1} - 1)T_t^{\sigma} G_t^{1-\sigma}$. Contrary to what happened in the leading country, in this case the growth rate increases with the distance to the technological frontier, as imitation is more productive the larger the technological gap. The lagging country thus grows faster than the technological leader and gets closer (at decreasing rates) to the frontier.

When the distance to frontier reaches the threshold $\widetilde{a}_h$, firms in the lagging country also begin innovating, as it now proves profitable for them to do so.[19] By combining the two activities firms maximize their productivity, and the growth rate of the lagging economy remains higher than the rate of expansion of the frontier ($\bar{g}$). The process of convergence continues until the distance to frontier reaches the level at which companies in the lagging country fully switch to innovation, i.e. until $a_{t-1} = \widetilde{a}_l$. Once the lagging country has reached this threshold, it makes use of the same production function as the leading country to increase productivity: the growth rates of the two countries are now equal, and the process of convergence is completed. These is summarized by the following:

Proposition 4.3. *In the absence of migration, the lagging country achieves convergence, and reaches the steady-state distance to frontier* $\widetilde{a}_l$.

Proof. See Section D.3 in the Appendix. □

The intuition behind this result is relatively straightforward: recall that firms always choose the composition of innovation/imitation that maximizes the rate of productivity growth, indeed, we know from Proposition 4.2 that in the absence of migration the market outcome is growth maximizing. When a country is lagging away from the frontier, i.e. when the distance-to-frontier parameter a_{t-1} is larger than $\widetilde{a}_l$, it is advantageous for firms to perform at least some imitation and not to fully specialize in innovation: firms exploit the higher productivity of imitation (away from the frontier) relative to innovation, for any given level of the relative supply of skills. Thus, as long as there is some gains to be earned by imitating, the average productivity (and hence the growth rate) will be higher for the lagging country than for the leading country. At any distance from the frontier larger than $\widetilde{a}_l$, the lagging country has a growth rate higher than $\bar{g}$ and the technological distance that separates it from the frontier tends to decrease.

This catching-up effect, reminiscent of similar effects in the technology diffusion literature (see, e.g. Barro and Sala-i-Martin (2004), chpt. 8), vanishes when the technological gap disappears. When there are no longer advantages to be derived from imitation, innovation is the only means to foster productivity; full specialization occurs (see Proposition 4.1), and convergence to the group of technological leaders has been accomplished.

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[19] As discussed in the proof of Proposition 4.1 in Appendix D.1, the value of $\widetilde{a}_h$ and $\widetilde{a}_l$ only depend on the values of the production elasticities, and on the equilibrium levels of ω_G and ω_T, that are both independent of a_{t-1}.

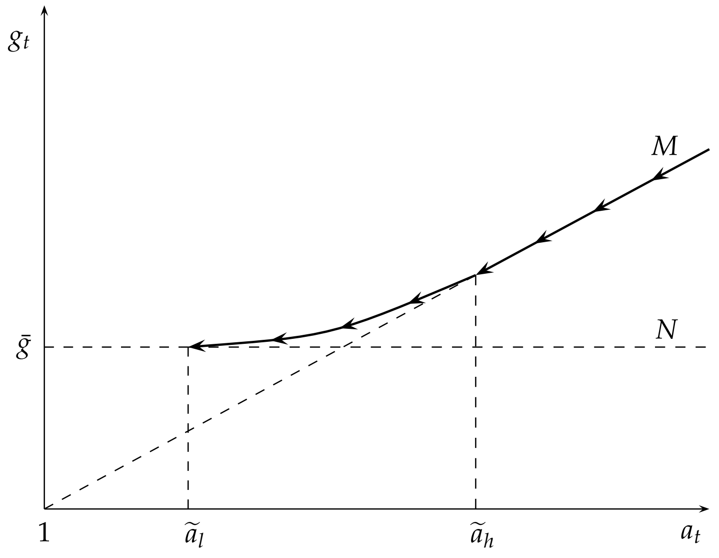

Figure 4.5: *Convergence without migration.*

Graphically, this is presented on the (a_t, g_t) plane in Figure 4.5. The horizontal dashed line N, stands for the growth rate of the innovating, frontier country, $\bar{g}$. The upward-sloping line M describes the growth rate reported by the economy that employs technological adoption as its only means to increase productivity. This line slopes upwards because of the increasing benefits of lagging behind the frontier, as discussed above. The solid lines with arrow represents the lagging economy's process of convergence towards the frontier, through the three different phases of imitation-only (the straight part of the solid line), imitation-innovation (the curved part) and innovation-only, when it reaches the distance $a_t = \widetilde{a}_l$, where convergence is complete.

4.5 Migration and distance to frontier

We now turn to analyzing the effects of the possibility of migration on the growth rate of the lagging country, and on its steady-state level of income.

Assume that both G-skilled and T-skilled workers in the lagging country have some non-negative, exogenous probability, p_G and p_T respectively, to migrate to the more developed leading country. We assume that migration is random, i.e. there is no possibility of screening potential migrants, and hence workers of each type face the same probability of migration. First, we study the case when the probability of migration is the same for both types of workers. Next, we analyze what happens when one type is favoured by the destination country, i.e. when agents of a given type have a higher probability of migrating.

4.5.1 Uniform probability of migration

Suppose that both types of skilled agents G and T have the same chances to migrate to the frontier country: i.e. having acquired their skills, workers will be able to offer their labour services abroad with probability $p_G = p_T = p \in (0, 1)$.

The possibility of migration influences the accumulation decisions of workers only in the source country. Indeed, since wages in the lagging country are lower than in the leading one, migration proves unappealing to skilled workers from the leading country. In the lagging country, however, rational workers will take into account that with some probability they will be able to migrate to the more advanced country and obtain higher wages.

In this context, the condition for the marginal worker in the destination country reads:

$$(p\, a_{t-1}\, \bar{\omega}_{Tt} + (1-p)\omega_{Tt})\, \xi = (p\, a_{t-1}\, \bar{\omega}_{Gt} + (1-p)\omega_{Gt}) j'. \tag{4.15}$$

Recalling the expression used in (4.2) to identify the indifferent worker,

$$j' = \sqrt{1 - 2\, G_t},$$

we immediately see that (4.15) implicitly expresses the supply of G-skilled labour in the source country, for any level of p and a_{t-1}. In a graph similar to the one in Figure 4.4, the supply curve under migration is characterized by a lower level of ω than the original curve S, for each level of G. Indeed, for workers to supply any level of G-skills (smaller than $\bar{G}^*$) the domestic relative wage has to be lower than before, given that the relative wage abroad is never lower than at home. Figure 4.6 presents the relative graph. Notice that in the specific case where the migration probability is the same for both types of workers, the two lines coincide when both countries specialize in innovation (at point $\bar{E}$ in the figure).[20]

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[20] From equation (4.15), it is possible to rewrite the supply of G-skills in terms of ω as $\omega = \omega_{\text{no-}\mu} - (\bar{\omega} - \omega_{\text{no-}\mu})\, \frac{p a \bar{\omega}_T/\omega_T}{1-p}$, where $\omega_{\text{no-}\mu} = \frac{\xi}{\sqrt{1-2G}}$ expresses the wage under autarchy, for each level of G. Since $\bar{\omega}$ is the maximum value for the equilibrium level of the relative wage, it follows that indeed, in the $(G,\, \omega)$ plane, the supply of G-skills under migration is below S for $a > \tilde{a}_l$, or, which is equivalent, for $G < \bar{G}^*$.

Firms' decisions to hire workers only depend on domestic conditions: given our assumption that the share of entrepreneurs is the same in the two countries, the number of workers per firm is the same in the two countries and across regimes. Thus, the possibility of migration does not affect the firms decision in any way: firms still maximize profits taking the wage level as given.

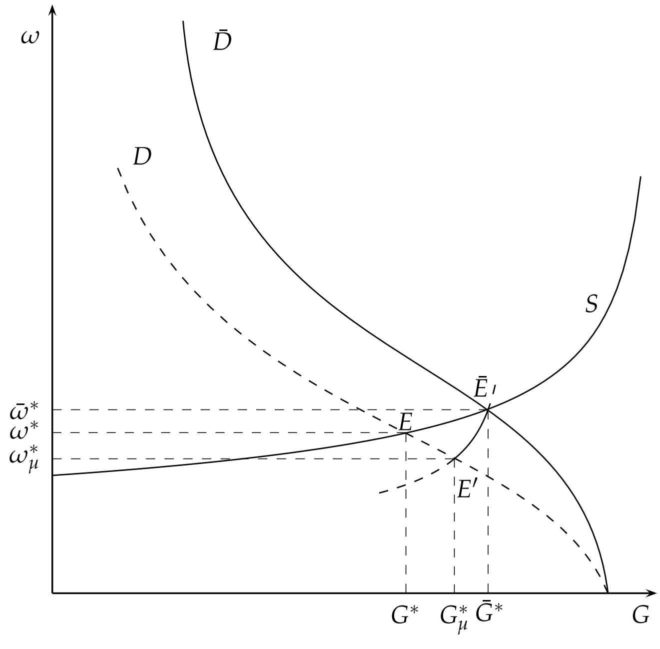

Figure 4.6: *Demand and Supply under Migration.*

As before, labour demand and labour supply jointly determine the equilibrium level of G and T. The probability of migration influences these equilibrium levels by distorting the accumulation incentives of the workers.

To understand why, remember that while workers respond to price incentives from both countries, firms only face domestic prices. Thus, at every equilibrium there will be a wedge between the wage ratio perceived by workers and the wages faced by firms. With the exception of point $\bar{E}$ where countries are *de facto* identical as refers to wage rates and technology, at every other migration equilibrium workers will perceive higher wage rates than firms. In particular the wage rate ω perceived by workers will be higher than the one perceived by domestic firms. This is due to the fact that the alternative to working at home is to work abroad, where only innovation takes place: since generalists are more productive than technicians in innovation, they are relatively more rewarded in the leading economy. Thus, workers naturally bias their decision towards G-skilled labour. From Figure 4.6, it is apparent that, with the exception of point $\bar{E}$, where only innovation occurs, every equilibrium point under migration will be characterized by a higher level of G-skills than the corresponding autarchy equilibrium. As this happens, the economy moves away from the growth-maximizing factor composition, T^*/G^* (see Proposition 4.2), at each level of the distance to frontier larger than $\widetilde{a}_l$. Hence, the growth rate of the source economy declines, leading to the following result:

Proposition 4.4. *When migration of skilled workers is possible, the growth rate of the lagging economy is reduced for all* $a \in (\widetilde{a}_l, \infty)$.

Proof. In text. □

As before, however, when the distance to frontier is $\widetilde{a}_l$, firms still specialize in innovation at point N; offer a relative wage equal to $\bar{\omega}^*$; and hire $\bar{G}^*$ workers. Indeed, when the probability to migrate is the same for both types of workers, the distortionary effect of migration decreases with the level of specialization in innovation, or which is the same, it increases with the distance to frontier, see (4.15). When the lagging country fully specializes in innovation, the possibility of migration ceases to play any role. In this situation the education incentives for agents are identical in both countries.

Elsewhere, however, things are more complicated. For firms it will still be profitable to combine innovation and imitation for any level of the distance to frontier larger than $\widetilde{a}_l$. The range (in terms of a) where the two activities coexist, however, is larger now than under autarchy. The supply of G-skills is in fact larger along the $E' - \bar{E}$ line than along the S line, for any ω. As a consequence, at $\widetilde{a}_h$ the level of G (and of T) will differ from its optimal level G^*. Hence, imitation only is not productive enough at $\widetilde{a}_h$ to justify full specialization in this activity. Specialization will necessarily occur at a level of a larger than $\widetilde{a}_h$, call it $\widetilde{a}_{h1}$, given that the productivity of imitation increases with the distance to frontier. This discussion leads us to our next result:

Proposition 4.5. *When migration of skilled workers is possible, and* $p_G = p_T = p$, *the lagging country converges at a steady-state distance to frontier equal to* $\widetilde{a}_l$.

Proof. See Section D.4 in the Appendix. □

The conclusion from this and from Proposition 4.4 is that when no type of skill is favoured by the leading country in terms of migration, the lagging country still converges to the same level of development as before the introduction of migration, but it does so at a slower rate than before.

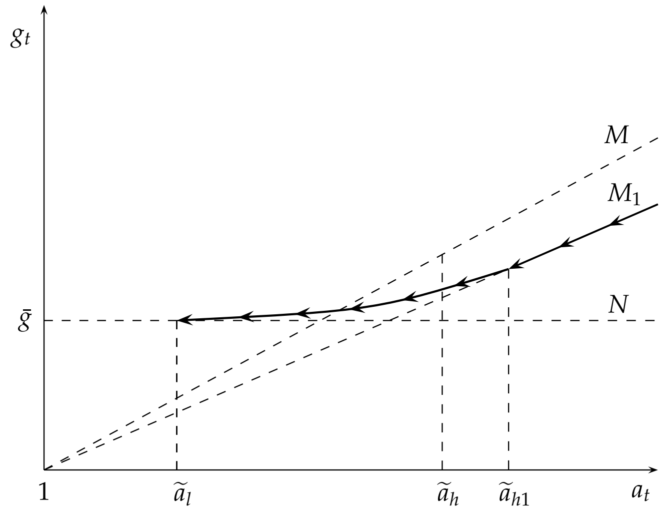

Figure 4.7: *Convergence with migration, and* $p_G = p_T$.

We can summarize the effects of the probability of migration in this situation as follows: in the first place migration distorts the accumulation of human capital reducing the growth rate (from imitation). Graphically, this is presented in Figure 4.7, where the downward sloping line M_1 is below the line M, that represents the growth rate without migration. Second, since imitation is now less productive *cœteris paribus*, firms will tend to begin innovating further away from the technological frontier. Indeed, the threshold value for innovation, $\widetilde{a}_h$, shifts right to $\widetilde{a}_{h1}$ in Figure 4.7.[21] Third, the process of convergence, however, continues up to the point $\widetilde{a}_l$, the same one as in the no-migration case, since the distortionary effect of migration is irrelevant when both countries specialize in innovation and the probability of migration is the same across workers' type.

4.5.2 Non-uniform probability of migration

In the previous subsection we have shown that, if both types of human capital have the same probability of migration, the lagging country achieves full convergence and the steady-state distance to frontier is $\widetilde{a}_l$. When the probabilities of migration differ across skill types, however, workers' incentives to accumulate skills are distorted to an even larger extent.

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[21] This can be easily seen from expression (D.2) in Appendix D.1. The introduction of migration makes technicians scarcer and reduces the relative wage faced by firms, since $\sigma > \phi$ this signifies an increase in the threshold level $\widetilde{a}_h$.

The analysis here parallels the analysis performed above for the case of uniform probabilities, with the exception that we assume that G-skilled workers, being more productive in innovation, will be more demanded in the frontier country than T-type workers and will accordingly face a higher probability of migration, i.e. we assume that $p_G > p_T$. Let us first rewrite (4.15), allowing for different probabilities of migration in different sectors:

$$(p_T\, a_{t-1}\, \bar{\omega}_{Tt} + (1 - p_T)\omega_{Tt})\, \xi = (p_G\, a_{t-1}\, \bar{\omega}_{Gt} + (1 - p_G)\omega_{Gt})\, j'. \tag{4.16}$$

As in the previous case, the probability of migration distorts the accumulation of human capital and reduces the growth rate, all else equal. Here, however, the fact that p_G is larger than p_T increases the expected value of accumulating G-skills to a larger degree. One of the consequences is that, in this case, the distortion affects the accumulation of skills also when the distance to frontier equals $\widetilde{a}_l$. Indeed, from equation (4.16), it is apparent that, even when workers face the same wages per unit of effective labour both at home and abroad ($\bar{\omega}_G$ and $\bar{\omega}_T$), the relative wage perceived by potential migrants is higher than $\bar{\omega}^*$, causing an over-supply of G-skills.

Moreover, the conclusions from Proposition 4.4 also hold in this case, and are further reinforced by the positive difference between p_G and p_T. Thus, the growth rate decreases further relative to the case where the probability of migration is expressed by the common p. From these two observation we can derive the following:

Proposition 4.6. *When migration of skilled workers is possible, and $p_G > p_T$, the steady-state distance to frontier of the sending economy increases. Moreover, complete specialization in innovation is never achieved by the lagging country.*

Proof. See Section D.5 in the Appendix. □

We use Figure 4.8 to complete the discussion of this case. The line M_2 in the figure lays strictly below the M line, which represents the growth rate without migration possibilities. However, based on our discussion above, we know that this line also lies below the line, M_1, that we used in Figure 4.7 to illustrate the case of common p.

The mechanism at work is the same as before: far away from the frontier it pays to concentrate skills in imitation, since this is the most profitable activity. The decrease in the distance to frontier, however, reduces the productivity gap between imitation and innovation. When the productivity has decreased enough, we observe a switch away from pure imitation. This happens for a

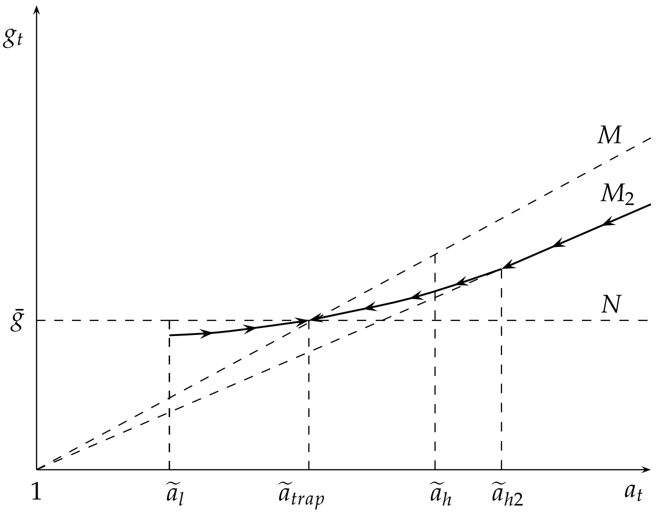

Figure 4.8: *No convergence with migration, and* $p_G \neq p_T$.

value of a equal to $\widetilde{a}_{h2} > \widetilde{a}_{h1} > \widetilde{a}_h$, given the existence of larger distortions in this context (the possibility of migrating *and* the different probabilities of doing so).

That the economy is distorted to a larger degree, finally, is evident from the fact that the lagging country experiences a *development trap* in this case. The fact that generalists are more favoured in migration means that technical skills become scarcer in the source country also at $\widetilde{a}_l$. Thus the growth performance of the lagging country cannot exceed the growth performance of the leading country (which is the speed of expansion of the frontier) at $\widetilde{a}_l$. By the continuity of the function expressing the growth rate, and the fact that it increases with the distance to frontier (see the Appendices for the details) we conclude that the process of convergence towards the frontier must stop short of $\widetilde{a}_l$. We identify this long-run rest-point of the system by $\widetilde{a}_{trap}$ in the Figure, to emphasize the suboptimal nature of this outcome. Despite having the potential to reach the other countries at the frontier, the distortions induced by the workers' migration prospects lock the country in a vicious circle of inappropriate accumulation of skills, lower economic growth (relative to potential) and persistently larger distance from the frontier.

4.6 The role of subsidies in the process of development

In the previous sections we have shown the effects of human capital's composition on the rate of economic growth and the potential convergence of a developing country. We concluded that the prospect of migration distorts the composition of human capital in the lagging countries and that, as a consequence, the brain drain translates into smaller growth rates and, potentially, into steady-states with larger gaps from the technological leaders.

A natural concern for policymakers in developing countries might then be to design policies aimed at correcting the distortions, and at adjusting the formation of human capital to the needs of local entrepreneurs. In this section we investigate one such instrument: targeted subsidies to education.

Under migration, the composition of human capital is suboptimal from the lagging country perspective, thus subsidies might be used as additional incentives to adopt the 'appropriate' type of skills. To off-set the negative impact of brain drain on human capital composition, policymakers in the lagging country could consider subsidizing the acquisition of technical education or, which is equivalent, taxing general skills. Without loss of generality, in what follows we consider subsidies to technical education.

Formally, we present subsidies as an increase in the returns to this type of education. Workers offering ξ units of technical skills on the market will receive a compensation of $w_T\,\xi(1+\tau)$, where $\tau > 0$ is the subsidy rate. Our modelling of subsidies provides a rather general representation of monetary transfers, in fact, every agent of type T works the same hours, and thus receives the same amount of subsidies.

To see how the subsidy to technical education corrects the distortionary effects of the possibility of migration, consider Figure 4.9.

In the figure we draw the expected income of agents accumulating T- and G-skills as a function of the agent's type, $j \in [0,1]$. Investment in T-skills requires $(1-\xi)$ units of time, irrespective of the agent's type. Hence, labour income equals $w_T\,\xi$ for any agent. The cost of accumulating G-skills, instead, depends on the type of the agent. An agent indexed by j must spend $(1-j)$ units of her time to accumulate capital. She can subsequently derive an income equal to $w_G\,j$ from her skills. Point A, the point where the horizontal $w_T\,\xi$ line crosses the sloping $(0-w_G)$ one, identifies j', the agent who's indifferent between the two types of skills. This point also determines the supply of G and T skills

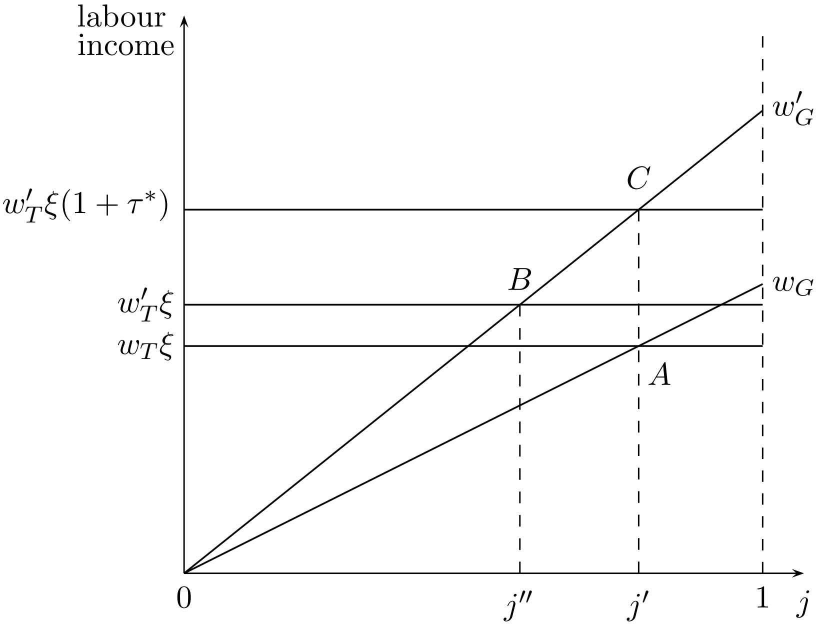

Figure 4.9: *Effects of a subsidy (τ) to technical education.*

according to (4.3) and (4.4).

In the absence of migration, this point determines the optimal supply (and composition) of skills. When migration possibilities enter the picture, however, expected wages increase for both skill types, and both schedules shift up. The wages raise from w_G to w'_G and w_T to w'_T. However, since G-skills are relatively more rewarded abroad, the upwards shift in the sloping line is more marked, the relevant curves now cross in B, and the indifferent agent has a lower index: j''. Accordingly, the supply of G-skills increases, while that of T-skills decreases. This yields a suboptimal result in terms of the availability of skills for domestic firms. As discussed in previous sections, this results in a reduction of the growth rate and, when $p_G > p_T$, in an increase of the long-run distance to frontier: a development trap.

Increasing the returns to accumulating technical skills tends to correct the distortion caused by the migration prospects. The provision of a subsidy increases the wages of T-skilled workers, and raises the horizontal line in the figure further up. When the subsidy is set optimally, the indifferent agent is once again indexed by j'. Since the subsidy does not distort the demand for skills, this is sufficient to repristinate optimality. For that to be the case, however, τ must be set equal to

$$\tau^* = \frac{\omega_{T\text{no-}\mu}}{\omega_{G\text{no-}\mu}} \cdot \frac{p_G\, a_{t-1}\, \bar{\omega}_{Gt} + (1 - p_G)\omega_{Gt}}{p_T\, a_{t-1}\, \bar{\omega}_{Tt} + (1 - p_T)\omega_{Tt}} - 1, \tag{4.17}$$

where the 'no-μ' subscript indicates the optimal wages without migration. When technical education is subsidized according to this rule, that is when $\tau = \tau^*$, the marginal agent j' faces the same expected relative returns to accumulating skills, irrespective of the regime of international mobility.

Notice that, since the strength of the distortion increases with the distance to frontier, the optimal subsidy τ^* is an increasing function of a_{t-1}. Indeed, recall that the relative wage ω_t decreases with the distance to frontier, going from $\bar{\omega}^*$ to ω^*, as can be clearly seen from Figure 4.4; thus, $\omega_{T\text{no-}\mu}/\omega_{G\text{no-}\mu}$ increases with a_{t-1}. Moreover, the relative domestic wage ω_{Gt}/ω_{Tt} decreases with the distance to frontier, as the productivity of G-skills decreases with the decreasing weight of innovation relative to imitation. Finally, $p_G > p_T$. Thus, also the second ratio at the right-hand side of (4.17) increases with a_{t-1}.

As the process of development and convergence to the frontier proceeds, the rate of the subsidy necessary to restore the optimal trajectory declines over time to satisfy (4.17) at each instant (and at each level of the distance to frontier a_{t-1}). We can summarize this discussion in the following result:

Proposition 4.7. *When technical skills are subsidized according to* (4.17)*, the optimal accumulation of skills is restored. Moreover, the optimal subsidy rate* τ^* *declines over time, as the technological frontier draws nearer.*

Proof. In the text. □

Thus, subsidizing technical education when the prospects of migration might distort accumulation incentives on the part of workers corrects the incentives and restores optimality. We view this implication of our model as an interesting rationalization of the policies performed by the successful East-Asian economies that we discussed in Section 4.1. There the state invested in specific types of tertiary education, with an eye (and something more) to the interests of the local employers. The implications of the model, moreover, seem consistent with the evolution of the attitude of the policymakers responsible for educational policy mentioned by some observers. The shift from interventionism to *laisser-fair* is in line with our story: when the structure of the economy changes to match that of the leading economies, direct interventions in education, to regulate the structure of the supply of skills become redundant, and the market mechanisms regain center stage.

4.7 Conclusions

The debate on the economic effects of the brain drain has not yet reached univocal conclusions under many respects. This is particularly true for studies focusing on developing countries. Recent empirical contributions (e.g. Beine, Docquier, and Rapoport 2003) have argued that among developing countries there are both winners and losers, and concluded that more theoretical work is needed to understand this pattern.

Building on these ideas, we develop a simple theoretical model to investigate whether the prospects of migration have an influence on growth and convergence. Our contribution extends the framework of Vandenbussche, Aghion, and Meghir (2006) to incorporate the endogeneity of human capital accumulation in a model where growth is driven by technical progress, and technical progress is the result of purposive activities of imitation and of *bona fide* innovation. The main insight from the model is that, at different levels of development, different types of human capital, or rather different proportion thereof, are needed to achieve optimal growth. Thus, the key determinant of the optimal composition of skills in any given economy is its distance from the technological frontier.

By blurring the borders between economic systems at different levels of development, the possibility of migration distorts price signals, induces change in the accumulation of human capital, and ultimately proves detrimental for developing countries. We find that the brain drain reduces the growth rate of a developing country along the transition to its long-run balanced growth path. Moreover, we point at the possibility of the emergence of development traps, as the opportunities of migration might reduce the long-run income level of lagging countries.

Our theoretical contribution also provides some normative conclusions that might shed more light on the astonishing performance of the most successful East Asian economies over the past few decades. From our positive analysis we know that some types of human capital are more important for the developing countries, but the incentives to acquire them are reduced by the prospects of migration. Hence, on the normative side, we show that a very important role can be played by government interventions, e.g. in the form of subsidies the encourage the acquisition of those particular skills which are most needed domestically. Moreover, since the distortionary impact of the migration prospects decline with the proximity to the frontier, the government's support in favor of certain skills should taper off as the development process proceeds.

We find this story particularly useful, as it can be used to rationalize the behaviour of the successful East Asian economies over their path to development. Countries like Japan, the Republic of Korea, Taiwan and Singapore all experienced both high rates of GDP growth and of brain drain at the same time: a puzzling story, at first sight. However, they are also quoted as examples of the government's intervention in the educational field, where policies were aimed at favouring the acquisition of technical skills over other skills. According to our story, these policies might have helped the growth performance of Japan and of the Asian Tigers by correcting the distortionary impacts induced by the brain drain. We find more support for the predictive power of our analysis in the fact that more recently the same countries are advocating a pervasive change in their educational strategies, to favour the autonomous display of market forces. This corresponds to the policy a regulator in our model would find optimal once the technological frontier has been reached.

Our analysis, however, raises a number of questions, the most obvious of which refers to the empirical relevance of the mechanisms we identify. We present some stylized facts and anecdotal evidence supporting our theory, yet, a more thorough empirical analysis is called for by our results. Among our plans for future work, finding the necessary data and testing the implications of the model necessarily plays a prominent role.

APPENDIX

D

PROOFS OF THE RESULTS

D.1 Proof of Proposition 4.1

Firms maximize profits choosing employment in productivity-enhancing activities, taking wages as given:

$$\begin{aligned}
\max_{\{T_{mt},T_{nt},G_{mt},G_{nt}\}} \pi_t = & \zeta \left[1 + T_{nt}^{\phi} G_{nt}^{1-\phi} + (a_{t-1} - 1)\, T_{mt}^{\sigma} G_{mt}^{1-\sigma}\right] + \\
& - \omega_{Gt} (G_{mt} + G_{nt}) - \omega_{Tt} (T_{mt} + T_{nt}) \,, \qquad \text{(D.1)} \\
s.t. \qquad & T_{mt} \geq 0,\ T_{nt} \geq 0,\ G_{mt} \geq 0,\ G_{nt} \geq 0.
\end{aligned}$$

Where we have normalized the expression for profits using the distance to frontier A_{t-1}, letting $a_{t-1} \equiv \bar{A}_{t-1}/A_{t-1}$. From the first-order conditions of this problem, we know that, for every level of the relative wages, the relative demand for skills in innovation and imitation must satisfy

$$\frac{T_{nt}}{G_{nt}} = \left(\frac{\phi}{1-\phi}\frac{\omega_{Gt}}{\omega_{Tt}}\right), \text{ and } \frac{T_{mt}}{G_{mt}} = \left(\frac{\sigma}{1-\sigma}\frac{\omega_{Gt}}{\omega_{Tt}}\right).$$

Plugging these back into (D.1), we obtain the following alternative expression:

$$\begin{aligned}
\pi_t = \zeta \left[\left(\frac{\phi}{1-\phi}\frac{\omega_{Gt}}{\omega_{Tt}}\right)^{\phi} G_{nt} + (a_{t-1} - 1)\left(\frac{\sigma}{1-\sigma}\frac{\omega_{Gt}}{\omega_{Tt}}\right)^{\sigma} G_{mt}\right] - \omega_{Gt}(G_{nt} + G_{mt}) + \\
- \omega_{Tt}\left(\frac{\phi}{1-\phi}\frac{\omega_{Gt}}{\omega_{Tt}} G_{nt} + \frac{\sigma}{1-\sigma}\frac{\omega_{Gt}}{\omega_{Tt}} G_{mt}\right).
\end{aligned}$$

The necessary conditions for a maximum read:

$$(1-\phi)\left(\frac{\phi}{1-\phi}\frac{\omega_{Gt}}{\omega_{Tt}}\right)^{\phi} \leq \omega_{Gt}, \qquad \left[(1-\phi)\left(\frac{\phi}{1-\phi}\frac{\omega_{Gt}}{\omega_{Tt}}\right)^{\phi} - \omega_{Gt}\right] G_{nt} = 0;$$

$$(a_{t-1}-1)(1-\sigma)\left(\frac{\sigma}{1-\sigma}\frac{\omega_{Gt}}{\omega_{Tt}}\right)^{\sigma} \leq \omega_{Gt},$$

$$\left[(a_{t-1}-1)(1-\sigma)\left(\frac{\sigma}{1-\sigma}\frac{\omega_{Gt}}{\omega_{Tt}}\right)^{\sigma} - \omega_{Gt}\right] G_{mt} = 0.$$

An interior solution for this problem obtains when the left-end sides of both inequalities above equal ω_{Gt}. Thus, both activities occur in equilibrium whenever

$$a_{t-1} = 1 + \frac{1-\phi}{1-\sigma}\left(\frac{1-\sigma}{\sigma}\right)^{\sigma}\left(\frac{\phi}{1-\phi}\right)^{\phi}\omega_t^{\phi-\sigma} \equiv \widetilde{a}(\omega_t). \tag{D.2}$$

That is, for every value of $\omega_t \equiv \omega_{Gt}/\omega_{Tt}$, there exists a unique value of a_{t-1}, such that an interior solution obtains. In other terms, the solution is characterized as follows:

$$\text{if } a_{t-1}\begin{cases} < & \widetilde{a}(\omega_t) & \Rightarrow & \text{innovation only;} \\ = & \widetilde{a}(\omega_t) & \Rightarrow & \text{innovation and imitation;} \\ > & \widetilde{a}(\omega_t) & \Rightarrow & \text{imitation only.} \end{cases} \tag{D.3}$$

However, from the discussion of the equilibria in Section 4.3, we know that at any equilibrium, the wage rate must lay in the interval $[\omega^*, \bar{\omega}^*]$. This implies bounds for the range of the values of a_{t-1} for which interior solutions may occur in the equilibrium. Let the lower bound of the interval be $\widetilde{a}_l = \widetilde{a}(\bar{\omega}^*)$ and the upper bound be $\widetilde{a}_h = \widetilde{a}(\omega^*)$.

Then, from (D.3), we can conclude that when $a < \widetilde{a}_l$ only innovation occurs. While $a_{t-1} > \widetilde{a}_h$, implies that firms only resort to imitation. For the intermediate range, $a_{t-1} \in (\widetilde{a}_l, \widetilde{a}_h)$, the equilibrium is characterized by firms performing both imitation and innovation.

To see this, imagine a situation where the distance to frontier is arbitrarily close to (but smaller than) $\widetilde{a}_l$. Then all firms innovate and the wage ratio equals $\bar{\omega}^*$. Now imagine that for some reason a_{t-1} increases to a value larger that $\widetilde{a}_l$, but smaller than $\widetilde{a}_h$. Every firm, given a wage ratio equal to $\bar{\omega}^*$ would prefer to shift to imitation, since they can increase profits through the shift. But all firms are symmetric and if all shift the wage rate becomes ω^*, at which level, firms would prefer to innovate. By iterating this reasoning, we can conclude that the only level of the wage rate consistent with an equilibrium is the one we identified by $\widetilde{\omega}(a)$. A symmetric reasoning is possible for the case where

a_{t-1} is arbitrarily close to $\widetilde{a}_h$ and, following a shock, comes to lie in the interval $(\widetilde{a}_l, \widetilde{a}_h)$. This concludes our proof. □

D.2 Proof of Proposition 4.2

Recall equation (4.7),

$$A_t = A_{t-1} + A_{t-1} T_{nt}^{\phi} G_{nt}^{1-\phi} + (\bar{A}_{t-1} - A_{t-1}) T_{mt}^{\sigma} G_{mt}^{1-\sigma};$$

the growth rate is:

$$g_t \equiv \frac{A_t - A_{t-1}}{A_{t-1}} = T_{nt}^{\phi} G_{nt}^{1-\phi} + (a_{t-1} - 1) T_{mt}^{\sigma} G_{mt}^{1-\sigma}. \tag{D.4}$$

The market solution implies that wages equal the marginal products of the two types of skills in both activities, using $G_{nt} + G_{mt} = G_t$ and $T_{nt} + T_{mt} = T_t$, we write this as:

$$\begin{aligned}\omega_{Gt} &= (1-\phi) T_n^{\phi} G_n^{-\phi} = (a_{t-1} - 1)(1-\sigma)(T_t - T_{nt})^{\sigma} (G_t - G_{nt})^{-\sigma};\\ \omega_{Tt} &= \phi T_{nt}^{\phi-1} G_{nt}^{1-\phi} = (a_{t-1} - 1)\sigma (T_t - T_{nt})^{\sigma-1} (G_t - G_{nt})^{1-\sigma}.\end{aligned}$$

Focusing on imitation, this implies:[1]

$$\frac{\omega_{Gt}}{\omega_{Tt}} = \frac{1-\sigma}{\sigma}\left(\frac{T_t - T_{nt}}{G_t - G_{nt}}\right).$$

In the absence of migration, this ratio must equal (4.3) in equilibrium, i.e.

$$\frac{1-\sigma}{\sigma}\left(\frac{T_t - T_{nt}}{G_t - G_{nt}}\right) = \frac{\xi}{\sqrt{1 - 2\,G_t}}. \tag{D.5}$$

Let G_t^* be the growth maximizing value of G_t:

$$G_t^* = \arg\max\ g_t\ = \arg\max\ \ T_{nt}^{\phi} G_{nt}^{1-\phi} + (a_{t-1} - 1)(T_t - T_{nt})^{\sigma} (G_t - G_{nt})^{1-\sigma};$$

since g_t is strictly concave and continuous, and T_t is a function of G_t according to (4.4), the sufficient condition for a maximum reads:

$$\frac{1-\sigma}{\sigma}\left(\frac{T_t - T_{nt}}{G_t - G_{nt}}\right) = -\frac{\partial T(G_t)}{\partial G_t}. \tag{D.6}$$

From (4.4), it is straightforward that

$$-\frac{\partial T(G_t)}{\partial G_t} = \frac{\xi}{\sqrt{1 - 2\,G_t}}.$$

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[1] This is without loss of generality, focusing on innovation yields equivalent results.

Hence, (D.6) becomes

$$\frac{1-\sigma}{\sigma}\left(\frac{T_t - T_{nt}}{G_t - G_{nt}}\right) = \frac{\xi}{\sqrt{1-2\,G_t}}.$$

Since this expression is identical to (D.5), we conclude that the market outcome is growth maximizing. □

D.3 Proof of Proposition 4.3

From Proposition 4.1 we know that the lagging country can be in any of three situations: it can be performing innovation only (when $a \leq \widetilde{a}_l$), it can be engaging in both innovation and imitation (when $a \in (\widetilde{a}_l, \widetilde{a}_h)$), or it can be fully specialized in imitation (when $a \leq \widetilde{a}_h$). Under the innovation-only regime, the lagging country is, by symmetry, identical to the technological leader, and its growth rate will then be $\bar{g}$, a constant. If imitation and innovation coexist at the optimum, the growth rate will be given by (D.4). Proposition 4.2 shows that for each level of a_{t-1}, this function is maximized by the solution of our model. Moreover, the function in (D.4) is continuously differentiable in $a \in (\widetilde{a}_l, \widetilde{a}_h)$. Thus, applying the envelope theorem yields:

$$\frac{\partial g_t}{\partial a_{t-1}} = T_{mt}^{\sigma} G_{mt}^{1-\sigma} > 0$$

In the imitation-only case, equation (D.4) reduces to

$$g_t = (a_{t-1} - 1) T_t^{\sigma} G_t^{1-\sigma}, \tag{D.7}$$

and the same reasoning goes through. We can conclude that the growth rate of the lagging economy increases with the distance to frontier and is higher than the rate of frontier expansion at each point where $a > \widetilde{a}_l$. □

D.4 Proof of Proposition 4.5

First notice that when $p_G = p_T = p$ the labour supply of the lagging country, implicitly defined by (4.15), coincides with the one for the leading economy whenever $\omega = \bar{\omega}$. In this case, by symmetry, the two economies are identical and their growth rates are also equal. Hence when the lagging country, has a distance to frontier equal to $\widetilde{a}_l$, it specializes in innovation, and will grow at the same rate as the leading economy: $g_t = \bar{g}$.

Whenever $a_t \in (\widetilde{a}_l, \widetilde{a}_h)$, both innovation and imitation occur at the same time. The growth rate of the economy is then:

$$g_t(\cdot) = T_{nt}^{\phi} G_{nt}^{1-\phi} + (a_{t-1} - 1) T_{mt}^{\sigma} G_{mt}^{1-\sigma}.$$

In the presence of migration, the equilibrium level of G and T, and the split thereof, will not be the same as without migration, hence the growth rate will not be maximized.

Differentiating the above expression with respect to a_{t-1} yields:

$$\frac{\mathrm{d}g_t}{\mathrm{d}a_{t-1}} = \phi T_{nt}^{\phi-1} G_{nt}^{1-\phi} \frac{\partial T_{nt}}{\partial a_{t-1}} + (1-\phi) T_{nt}^{\phi} G_{nt}^{-\phi} \frac{\partial G_{nt}}{\partial a_{t-1}} + (a_{t-1}-1)\sigma T_{mt}^{\sigma-1} G_{mt}^{1-\sigma} \frac{\partial T_{mt}}{\partial a_{t-1}} + \\ + (a_{t-1}-1)(1-\sigma) T_{mt}^{\sigma} G_{mt}^{-\sigma} \frac{\partial G_{mt}}{\partial a_{t-1}} + T_{mt}^{\sigma} G_{mt}^{1-\sigma}. \tag{D.8}$$

At any interior equilibrium it must be the case that $\phi T_{nt}^{\phi-1} G_{nt}^{1-\phi} = (a_{t-1} - 1)\sigma T_{mt}^{\sigma-1} G_{mt}^{1-\sigma} = \omega_{TGt}$, and $(1-\phi) T_{nt}^{\phi} G_{nt}^{-\phi} = (a_{t-1}-1)(1-\sigma) T_{mt}^{\sigma} G_{mt}^{-\sigma} = \omega_{Gt}$. Moreover, since $T = T_{mt} + T_{nt}$, it follows that $\partial T_{nt}/\partial a_{t-1} = \partial T_t/\partial a_{t-1} - \partial T_{mt}/\partial a_{t-1}$; a similar expression holds for G_t, G_{mt} and G_{nt}. Using these facts into (D.8), we obtain,

$$\frac{\mathrm{d}g_t}{\mathrm{d}a_{t-1}} = \omega_{Tt} \frac{\partial T_t}{\partial a_{t-1}} + \omega_{Gt} \frac{\partial G_t}{\partial a_{t-1}} + T_{mt}^{\sigma} G_{mt}^{1-\sigma}.$$

Recalling the expression linking the supply of T-skills to G_t, from equation (4.4), we can rewrite $\partial T_t/\partial a_{t-1}$ as,

$$\frac{\partial T_t}{\partial a_{t-1}} = -\frac{1}{\sqrt{1-2G_t}} \frac{\partial G_t}{\partial a_{t-1}}.$$

Plugging this into the expression for $\mathrm{d}g_t/\mathrm{d}a_{t-1}$ finally gives us,

$$\frac{\mathrm{d}g_t}{\mathrm{d}a_{t-1}} = \left[\omega_{Gt} - \frac{\omega_{Tt}}{\sqrt{1-2G_t}}\right] \frac{\partial G_t}{\partial a_{t-1}} + T_{mt}^{\sigma} G_{mt}^{1-\sigma} > 0, \tag{D.9}$$

since both terms are always positive. Indeed, as discussed in section 4.5.1, the term in square brackets is always negative since the supply curve under migration, and hence the equilibrium value of the ware rate ω, lies below the supply curve relative to the no migration case. Recalling footnote 20 this implies $\omega_t < \omega_{\text{no-}\mu}$, or $\omega < \xi/\sqrt{1-2G_t} < 1/\sqrt{1-2G_t}$. Since $\partial G_t/\partial a_{t-1} < 0$ because the equilibrium level of G_t decreases with ω_t, while ω_t decreases with the distance to frontier, the first term is always positive. The positivity of the second term at the right-hand side, on the other hand, is trivial.

To conclude the proof notice that when only imitation occurs by a similar reasoning we immediately get (D.9), by setting $T_{mt} = T_t$ and $G_{mt} = G$.

Thus, we have shown that the lagging economy grows faster than the leading one for each level of the distance to frontier larger than $\widetilde{a}_l$, while it grows just at the same rate as the frontier when full specialization in innovation (i.e. convergence) is finally achieved. □

D.5 Proof of Proposition 4.6

Notice that the proof in Proposition 4.5 that the growth rate of the lagging economy increases with the distance to frontier holds irrespective of the values of p_G and p_T. Hence, also in this case we can conclude that g increases monotonically with a. Thus, there is a tendency for the technologically lagging country to converge.

To prove that the process stops prematurely when the probability of migration is different for workers with different types of skills, recall (4.16). If the distance to frontier were $\widetilde{a}_l$ and firms in the lagging country were to specialize in innovation, by symmetry, domestic wages would equal foreign ones. Contrary to before though, the two economies are not identical, given the wedge induced by the different probabilities of migration. Thus the accumulation of human capital is distorted. From Proposition 4.2, the growth rate is maximized in the leading country. Since g is strictly concave and continuous, it follows that the growth rate that can be obtained for $\widetilde{a}_l$ by the lagging country can only be smaller than $\bar{g}$.

Since the growth rate increases monotonically with a, it follows immediately that the lagging country will stop converging towards the frontier at a level of the distance to frontier $a_{trap} > \widetilde{a}_l$.

Thus, the steady-state distance to frontier is increased by the possibility of migration and that no specialization in innovation is possible in this case. □

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NEDERLANDS SAMENVATTING

De richting kiezen: investeren, het milieu, en economische ontwikkeling

Is technologische verandering goed voor het milieu in een globaliserende wereld, of leidt het daarentegen tot meer vervuiling? Is klimaatbeleid een verlichte poging om het milieu te behouden voor toekomstige generaties, of is het slechts een last voor de economie? Leiden pogingen om het onderwijsniveau in ontwikkelingslanden te verhogen tot hogere economische groei, of worden daarmee toch al schaarse middelen weggegooid? Dit zijn slechts enkele van de thema's die in deze dissertatie worden onderzocht.

Dit proefschrift concentreert zich op de relaties tussen technologische verandering, milieubeleid en milieukwaliteit enerzijds, en op de relaties tussen technologische verandering, de accumulatie van menselijk kapitaal en economische ontwikkeling anderzijds. Door dit hele boek heen betogen we dat we, om deze complexe fenomenen te begrijpen, rekening moeten houden met zowel de algemeen evenwichtseffecten van deze problemen, zoals de wederkerige verbanden tussen technologische verandering en het aanbod van productiefactoren (zoals natuurlijke hulpbronnen en vaardigheden), als met de dynamische aspecten, zoals de ontwikkeling over de tijd van het niveau en de samenstelling van technologie en productiefactoren. In dit proefschrift nemen we dit als uitgangspunt en bestuderen we uiteenlopende onderwerpen zoals *pollution havens* die het gevolg zijn van handel tussen Noord en Zuid, internationale verschillen in klimaatbeleid en innovatie, en de verbanden tussen migratie, technologische ontwikkeling en groei in ontwikkelingslanden.

Onze analyse wordt uitgevoerd met behulp van dynamische algemeen evenwichtsmodellen, met kennisaccumulatie die wordt gedreven door financiële prikkels, en is dus stevig geworteld in de traditie van de groeitheorie. De vier hoofdstukken die samen dit proefschrift vormen hebben echter alle een speciale focus op de rol van de *samenstelling* van productiefactoren, in plaats van op hun *niveau*, in het bepalen van de uitkomsten.

De eerste drie hoofdstukken van dit boek vallen binnen het raamwerk van ‘Directed Technical Change‘ (gerichte technologische verandering, DTC), één van de meest recente ontwikkelingen op het terrein van de theorie van economische groei. De ontwikkeling van deze benadering is gestart door Daron Acemoglu, die het belang van de *richting* en de *bias* (strekking) van endogene technologische verandering benadrukt (zie bijvoorbeeld Acemoglu 2002). In de eerste drie hoofdstukken van deze dissertatie breiden we het DTC kader uit, en analyseren we verschillende onderwerpen op het terrein van milieu-economie. Als eerste behandelen we het debat rond de *Pollution Haven Hypothesis* (hypothese van toevluchtsoorten voor vervuiling).

Het eerste hoofdstuk van dit proefschrift richt zich op de rol van endogene technologische verandering en technologie spillovers bij het verklaren van verschillen in vervuiling tussen landen, en het *Pollution Haven effect* van internationale handel. We presenteren een Noord-Zuid handelsmodel met twee specifieke eigenschappen. Ten eerste worden nieuwe technologieën ontwikkeld in het Noorden, om pas daarna naar het Zuiden te verspreiden. Ten tweede kiezen milieu-autoriteiten in iedere regio lokaal milieubeleid door een afweging te maken tussen een hoger inkomen en het verlies aan nut door meer vervuiling.

We tonen aan dat handel er toe kan leiden dat het Noorden technologieën ontwikkelt die besparen op vervuiling en dat het Zuiden minder vervuilt, hetgeen tegen de traditionele herallocatie-en specialisatie-effecten van handel in gaat. Dit ’technologie optimisme’ is echter niet de enige mogelijke uitkomst. Indien het moeilijk is om van vervuiling-intensieve goederen weg te substitueren, leidt een toename in innovatie inspanningen in de schone sectoren in het Noorden tot een toename in de vraag naar vervuiling-intensieve goederen in het Zuiden. In dit geval leidt handel tot technologische verandering die juist vervuiling gebruikt, en dit versterkt de prikkel voor het Zuiden om meer te vervuilen.

Verspreiding van technologieën van het Noorden naar het Zuiden is dus niet noodzakelijk goed voor het milieu in het Zuiden. Door DTC in de analyse op te nemen tonen we aan dat, in tegenstelling tot wat vaak wordt beweerd, technologische verandering slechts potentieel, en niet noodzakelijk, een zegen is.

In het tweede hoofdstuk van deze dissertatie gaan we verder met onze analyse van DTC in open economieën en richten we onze aandacht op klimaatbeleid en het Kyoto Protocol. Het hoofdstuk richt zich op het debat over de effectiviteit van het Protocol indien sprake is van grote landen die het Protocol niet geratificeerd hebben. De crux is dat landen die buiten een internationaal klimaatverdrag vallen prikkels kunnen hebben om hun uitstoot van broeikasgassen te verhogen, terwijl andere landen juist proberen hun emissies te verlagen. Dit fenomeen heet *carbon leakage* (koolstof lekkage).

We betogen dat tot op heden de rol van technologische verandering in het debat zwaar onderschat is. We ontwikkelen een twee landen model waarin innovaties endogeen plaatsvinden in beide regio's, en we vergelijken het effect van een unilaterale limiet op CO_2 uitstoot op de emissiebeslissing van het andere land. We tonen aan dat het toestaan van endogene verschillen tussen sectoren in de mate van technologische verandering, dat wil zeggen indien sprake is van DTC, de perceptie van het probleem drastisch verandert. We wijzen op het feit dat klimaatbeleid de prikkels voor innovatie verandert, door veranderingen in de relatieve prijzen (en het relatieve aanbod) van de productiefactoren. In vergelijking met het geval van niet-gerichte technologische verandering leidt DTC tot minder toename in de CO_2 uitstoot van het andere land. Daarnaast tonen we aan dat, onder bepaalde omstandigheden, de richting van carbon leakage omgekeerd kan worden, en de introductie van het Kyoto Protocol kan leiden tot technologieën die niet-ratificerende landen ertoe brengen hun emissies te verlagen.

In het derde hoofdstuk richten we onze aandacht op het onderwerp duurzaamheid, dat wil zeggen de vraag of economische groei op lange termijn kan aanhouden indien sprake is van schaarste van natuurlijke hulpbronnen. De meeste aandacht in de literatuur op dit terrein gaat uit naar de vraag of technologische vooruitgang een blijvend niveau van consumptie kan garanderen. De gezamenlijke noemer van de oude en de nieuwe modellen is dat een strikt positieve groeivoet van hulpbron aanpassende (*resource augmenting*) technologische vooruitgang noodzakelijk is voor niet-afnemende consumptie op de lange termijn. In alle endogene groei modellen met niet-hernieuwbare hulpbronnen is een noodzakelijke voorwaarde voor altijd-toenemende consumptie dat de groeivoet van hulpbron aanpassende technologische vooruitgang strikt groter is dan de discontovoet van consumptie. Hetzelfde geldt voor neo-klassieke modellen waar de mate van hulpbron-besparende technologische verandering exogeen is. De meeste bijdragen op dit terrein delen dus de mening dat innovaties direct of indirect de productiviteit van natuurlijke hulpbronnen verhogen. Het *bestaan* van puur hulpbron aanpassende technologische verandering ontbeert tot nu toe echter nog iedere microfundering. Men kan dus bij bovengenoemde modellen aantekenen dat ze conceptueel een afwijking hebben ten faveure van duurzaamheid: aangezien technologische verandering in principe kapitaal- in plaats van hulpbron aanpassend kan zijn, maken deze auteurs misschien slechts een doelmatige doch sterke aanname.

In dit hoofdstuk onderzoeken we of, en onder welke voorwaarde, technologische verandering endogeen gericht is op hulpbron aanpassende innovaties. We behandelen dit onderwerp met behulp van een multi-sector DTC raamwerk waarin niet-hernieuwbare hulpbronnen en accumuleerbaar fysiek kapitaal beide essentieel voor productie zijn.

Ons belangrijkste resultaat is dat langs een gebalanceerd groeipad puur hulpbron aanpassende technologische verandering plaatsvindt: hoewel de groeivoet van kapitaal aanpassende (*capital augmenting*) technologische verandering op korte termijn positief kan zijn, moet ze naar nul dalen wanneer de economie het gebalanceerde groeipad bereikt. Zodoende bieden wij een microfundering voor modellen met kapitaal en een natuurlijke hulpbron met hulpbron aanpassende technologische verandering, voor zowel de Solow-Ramsey modellen als de modellen met endogene technologische verandering. Ons resultaat gaat in tegen de gedachte dat zulke modellen te optimistisch zijn met betrekking tot duurzaamheid.

Het vierde essay van dit proefschrift brengt ons op het terrein van ontwikkelingseconomie. In dit laatste hoofdstuk dragen we bij aan het debat rond het effect van de accumulatie van vaardigheden (*skills*) op groei: we analyseren de interactie tussen de samenstelling van vaardigheden, de mogelijkheid tot emigratie, en de mate waarin een ontwikkelingsland achter ligt.

In dit hoofdstuk breiden we het werk van Vandenbussche, Aghion en Meghir (2004) uit door endogene accumulatie van menselijk kapitaal toe te staan, en door ons te concentreren op de verstorende effecten van migratie in een model dat zich kenmerkt door een stroom naar het buitenland van geschoolde werkers, de zogenoemde *brain drain*.

Gemotiveerd door het niet eenduidige empirische werk van Beine, Docquier en Rapoport (2003) dragen we in dit hoofstuk bij aan het debat door ons te concentreren op de rol die de *samenstelling* van menselijk kapitaal speelt bij het voeden van de productiviteitsgroei en, uiteindelijk, de economische ontwikkeling. We betogen dat niet alle menselijk kapitaal *bruikbaar* is voor de beschikbare technologie en het huidige niveau van ontwikkeling. We betogen met name dat de afstand tot de technologische grens de sleutelfactor is voor het begrip van de effecten van de accumulatie en samenstelling van menselijk kapitaal op economische groei. Hoewel de accumulatie van menselijk kapitaal lijkt te leiden tot snellere technologische vooruitgang en economische groei wijzen wij op de verschillende *soorten* menselijk kapitaal die het meest bruikbaar zijn in verschillende stadia van economische ontwikkeling. Dit perspectief geeft de gedachte weer dat technologische veranderingen beschikbaar komen door hetzij immitatie hetzij innovatie, en dat iedere activiteit (een andere combinatie van) verschillende soorten van vaardigheden verlangt.

Onze resultaten laten zien dat de mogelijkheid van emigratie de prikkels voor agenten om het voor het land van oorsprong meest bruikbare soort menselijk kapitaal (gegeven het niveau van ontwikkeling) te verkrijgen, verstoort. We tonen aan dat de groeivoet van het land van oorsprong afneemt wanneer in vroege stadia van ontwikkeling emigratie mogelijk is. Ook bespreken we de voorwaarden waaronder het mogelijk is dat dit proces leidt tot een armoedeval, dat wil zeggen een situatie waarin het proces van convergentie naar de technologische grens voortijdig stopt.

Tenslotte richten we ons op een normatieve analyse en tonen we aan dat onderwijsbeleid, in de vorm van subsidies voor bepaalde vaardigheden, de negatieve effecten van migratie op groei tegen kan gaan. Landen die hun convergentiepotentieel wensen te maximaliseren dienen dus rekening te houden met dit mechanisme, en dienen de meest bruikbare vaardigheden in toenemende mate te subsidiëren naar mate de economie verder van de technologische grens af ligt en naar mate het gemakkelijker is om te emigreren.