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**THEORETICAL ESSAYS ON AN OPEN ECONOMY:  
MIGRATION, RESOURCES AND THE ENVIRONMENT**

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# Thesis Summary

This dissertation addresses two broad topics in the field of international economics and therefore consists of two parts. The first part is devoted to international migration of labor. This topic has been extensively debated by policymakers and the media in the last few decades, especially in the receiving, mostly advanced, countries. Migration flows from the developing and transition economies to the industrialized economies have increased drastically and contributed to the growing concern about the change in factor rewards in the receiving countries. That led the latter to introduce various barriers to entry, especially of unskilled workers. With the increasing complexity of overcoming these barriers, migrants rely more and more on services of illegal enterprises specialized in moving humans across international borders. This, in turn, led to a surge in undocumented migration and also debt-bonded migration - when the migrant was unable to pay for the moving cost upfront. Migration of skilled individuals has also been a hot topic of public debate. Developing countries, who heavily subsidize education of their population, point to a problem of losing their highly educated people when they get attractive work contracts in the developed economies. This concerns, for instance, the health sector. Part I of the thesis consists of three chapters, which are devoted, respectively, to the analysis of (i) saving behavior of undocumented migrants, (ii) optimal choice between debt-bonded and self-financed migration, (iii) cooperation between source and host countries on skilled-worker migration.

The second part deals with issues related to (i) investment in research and development of renewable substitutes for a non-renewable resource under un-

certainty; and (ii) conditions for a voluntary compliance with environmental regulations by developing countries. Invention of a substitute (or a backstop) is uncertain by definition. The question is then: What is the optimal investment rate in an R&D project which may lead to a breakthrough, given that the investment rate can affect the probability of success? History provides examples of countries that initiated investments in new technologies but were not able to follow through, while other countries were able to succeed. This is the case, for instance, of Holland which started ambitious investment in windmills but due to the lack of financing had to abandon the ongoing projects. By contrast, Germany and Denmark designed their investment strategy in such a way that the most innovative firms could obtain the necessary funds. These two countries then became the leaders of wind power production and even built their windmills in Holland. Thus, access to financing may play an important role for a success of a project under uncertainty. One of the articles of this dissertation looks at the role of access to international lending and borrowing when a country is engaged in development of a renewable substitute whose arrival follows a stochastic process. The last chapter discusses the condition/policies that should be in place in order to induce a developing country to voluntarily comply with environmental regulation.

# Résumé

Cette thèse porte sur deux grands thèmes dans le domaine de l'économie internationale et se compose donc de deux parties. La première partie est consacrée à la migration internationale de main-d'oeuvre. Ce sujet a été au centre des débats politiques et dans les médias pendant quelques dernières décennies, en particulier dans les pays d'accueil dont la plupart sont les pays avancés. Les flux migratoires en provenance des économies en voie de développement et en transition aux économies industrialisées ont considérablement augmenté et ont contribué à l'inquiétude croissante concernant le changement de la rémunération des facteurs de production dans les pays d'accueil. Cela a conduit ces derniers à introduire diverses barrières à l'entrée, en particulier des travailleurs non qualifiés. Avec la complexité croissante de surmonter ces obstacles, les migrants s'appuient de plus en plus sur les services d'entreprises illégales spécialisées dans le déplacement des humains à travers les frontières internationales. Ceci, à son tour, a conduit à une forte augmentation de la migration clandestine et de la migration par endettement (souvent proche de l'esclavage) - lorsque les migrants n'étaient pas capable de payer le coût de migration à l'avance. La migration des personnes qualifiées a également été un sujet de grands débats publics. Les pays en voie de développement, qui subventionnent fortement l'éducation de leur population, pointent sur un problème de perte de leurs personnes hautement qualifiées quand elles obtiennent des contrats de travail attractifs dans les pays développés. Cela concerne, par exemple, le secteur de la santé. Partie I de cette thèse se compose de trois chapitres qui sont consacrés, respectivement, à l'analyse de (i)

comportement d'épargne des migrants illégaux, (ii) le choix optimal entre la migration par endettement et l'autofinancement de la migration, (iii) la coopération entre les pays d'origine et les pays d'accueil sur la migration des travailleurs qualifiés.

La deuxième partie traite des questions liées à (i) l'investissement dans la recherche et le développement de substituts renouvelables pour une ressource non-renouvelable dans une situation d'incertitude, et (ii) les conditions d'un respect volontaire des règlements environnementaux par les pays en voie de développement. L'invention d'un substitut (ou d'un backstop) est par définition incertaine. La question est alors: Quel est le taux d'investissement optimal dans le R&D qui pourrait conduire à une invention, étant donné que le taux d'investissement peut influencer la probabilité de succès? L'histoire fournit des exemples de pays qui ont lancé des investissements dans les nouvelles technologies, mais n'ont pas pu aller jusqu'au bout, tandis que d'autres pays ont réussi. C'est le cas, par exemple, de la Hollande qui a commencé d'ambitieux investissements dans les éoliennes, mais en raison du manque de financement a dû abandonner les projets en cours. En revanche, l'Allemagne et le Danemark ont conçu leur stratégie d'investissement de manière à ce que les entreprises les plus innovantes pourraient obtenir les fonds nécessaires. Ces deux pays sont alors devenus les leaders de la production d'énergie éolienne et même construit leurs moulins à vent en Hollande. Ainsi, l'accès au financement peut jouer un rôle important pour le succès d'un projet incertain. Un des articles de cette thèse se penche sur le rôle de l'accès aux marchés des capitaux quand un pays est engagé dans le développement d'un substitut renouvelable dont l'arrivée suit un processus stochastique. Le dernier chapitre examine les conditions/politiques qui devraient être mises en place afin d'inciter les pays en voie de développement à se conformer volontairement à la réglementation environnementale.

# Chapter 1

## Introduction

This dissertation studies two broad topics, each of which is a frequently discussed and, to some extent, a sensitive issue in current policy debate. The first topic concerns with movement of people across international borders. The second topic concerns with preservation of global environment. Both topics, although seemingly unrelated, have in common the problem of optimal management of a resource, be it the problem of allocating a stock of labor across countries, or a stock of a non-renewable resource in time, and consequently, the techniques of analysis employed to study these problems are similar. Let me first discuss the issues related to the first topic and define the research questions addressed in this study.

## International Migration

Migration flows from one country to another have witnessed a surge ever since the means of transport improved drastically, thereby bringing down the cost of moving. The main motivation for the move is, in most cases, a search for better employment opportunities and improvement in the standard of living. Why are we - researchers - interested in international migration? The reasons are multiple. The first, and the most obvious, reason is that, at the macro level, migration of people represents a reallocation of inputs of production -

unskilled and skilled labor - from one country to another, leading to a change in the aggregate supply of these inputs. Consequently, all the factor rewards are affected. Secondly, at the micro level, a migrant is also a consumer and a saver. Consumption pattern of a migrant is in general very different from a consumption pattern of a native worker<sup>1</sup> and the same is true about the saving pattern. The difference depends, to a large extent, on how long the migrant can or expects to stay in the foreign country. If migration is temporary, migrants will tend to save more but also remit money to their families left behind in the source country. The volume of these asset flows is considerable and undoubtedly has impact on the economies that receive them. According to the World Bank, in El Salvador, Haiti, Jamaica and Jordan, for example, they reached more than 20% of GDP in 2007, while in Tajikistan they made up as much as 45.5%.<sup>2</sup> In 2008, 192 million foreign workers sent \$328 billion from developed to developing countries, which is almost triple the amount of official aid flows from OECD member states (World Bank, 2009). Remittances and repatriated savings finance not only everyday consumption but also investment in physical and human capital, thus affecting both directly and indirectly the receiving country's development path.<sup>3</sup> It is therefore important to improve our understanding of the determinants of these flows and hence the saving behavior of migrants who generate them.

Immigration of people, however, is not always unrestricted, especially nowadays. The largest migration flows observed today are from the developing to the developed economies. In an effort to control these flows advanced countries have introduced over the last couple of decades various barriers to international mobility, especially with respect to low-skilled workers. And even highly-skilled individuals face various quotas or constraints on the duration of

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<sup>1</sup>See, e.g., Djajić (1989).

<sup>2</sup>World Bank <http://blogs.worldbank.org/peoplemove/remittance-flows-to-developing-countries>.

<sup>3</sup>See Adams (1991), Durand et al. (1996), Lucas (2005), Massey and Parrado (1998), McCormick and Wahba (2001), and Taylor (1987).

stay and employment abroad. With the increasing complexity of overcoming these barriers, migrants are relying more and more on the services of human smuggling organizations to help them reach their desired destination. The last couple of decades have witnessed a surge in illegal immigration to the developed countries but also to rapidly growing developing economies in East Asia and elsewhere. The International Organization for Migration estimates that up to one half of migrant workers in developed countries are unauthorized (IOM 2003). Each year, the stock of undocumented migrants in the EU is estimated to be growing by 500'000 individuals (IOM 2004). Inflows of similar magnitude are reported for the U.S.A., with the stock of undocumented immigrants estimated at roughly 10.8 million in the first quarter of 2009 (Center for Immigration Studies 2009). As reported by Petros (2005), the fees for smuggling services vary depending on the distance traveled, the means of transport, and the entry strategy. They range from hundreds of dollars for an assisted crossing of a single border to tens of thousands of dollars on certain long-haul routes. Although the amounts paid to smugglers may not be very large in relation to the expected income abroad, from the perspective of low-skilled workers in the poor developing countries, the cost of migration represents a big obstacle that stands in the way of their migration plans.<sup>4</sup> A key question is how to pay for the cost of migration. One possibility

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<sup>4</sup>There is a growing empirical literature that offers evidence on the effects of liquidity constraints on international migration. Angelucci (2004) uses data from the Progreso program in Mexico to study the impact of transfers to liquidity-constrained, rural households on both internal and international migration. She finds that unconditional cash transfers are associated with a 60% increase in the average migration rate, while the likelihood of having migrants in the household is a positive function of the amount received through the program. In the case of El Salvador, Halliday (2006) reports that higher household wealth is positively associated with migration to the U.S.A. For internal migration in Russia, Andrienko and Guriev (2004) find evidence that inter-regional migration is constrained by lack of liquidity and that it rises with an increase in income. All these studies point to the importance of liquidity constraints in restricting contemporary international migration, confirming what we already know about the role of such constraints in the 18th and 19th centuries (see, e.g., Hatton and Williamson (1992, p.7) and Chiswick and Hatton (2006,



is to accumulate enough savings out of income earned in the source country. We would expect this "self-finance" solution to be attractive when the cost of migration is low in relation to the source-country wage. When the cost is in the tens of thousands of dollars, as in the case of undocumented migration from China to Western Europe and North America, there may be no scope for accumulating the required amount out of the income earned at home. In such cases it would be necessary to borrow in order to migrate. Borrowing can take place from a network of family and friends, part of which may already be located in the host country, or by getting indebted to a human smuggling organization. When borrowing from relatives or friends, the loan agreement is typically informal, with the interest obligations (if any) and the contract-enforcement mechanism varying from one culture to another. By contrast, when a migrant borrows from a smuggling organization, enforcement is very strict and the rates of interest are often 20%, 30% or even 60% per annum.<sup>5</sup> These rates reflect not only the risk incurred by the lender but also the high transactions and enforcement costs. As a way of controlling these costs, the smuggler typically obliges the migrant to become a bonded laborer with (a partner of) the smuggling organization until the loan is paid off. While in bondage, the migrant's freedom of movement is limited and the wage earned is usually lower than the free-market wage in the host country.<sup>6</sup>

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p.2)). See also Grubb (1985), Galenson (1984), and Hatton and Williamson (1994, 1998).

<sup>5</sup> See Kwong (1997, p.38), Gao (2004, p.11) and Sobieszczyk (2000, p.412). In the case of Chinese migrants to the West, interest rate of 2% per month is most common.

<sup>6</sup>As noted by the US State Department, indentured migrants were put to work "...at lower than minimum wage and used most of their savings to pay down their debt at usurious interest rates." [United States Department of State (2006)]. According to Jordan (2011): "An example of a debt bondage situation is a person who agrees to repay a debt of \$5000 for recruitment fees and travel costs allegedly paid by the employer/enforcer. The worker agrees to sew clothes until this 'debt' is repaid. The market wage for the work is \$50 per day but the employer/enforcer only deducts \$20 a day from the debt..." See Gao and Poisson (2005), Human Rights Watch (2000), Kwong (1997), Salt (2000), Sobieszczyk (2000), Stein (2003), Surtees (2003), and Vayrynen (2003) for informative discussions of the conditions facing migrants in debt bondage.

Another key question is whether the saving behavior of an illegal immigrant differs from that of a legal one and how. The answer to this question has direct implications for the design of immigration policies and in particular policies related to controlling illegal inflows. Deportation policies and levels of enforcement vary across nations. The somewhat lenient measures applied in the U.S.A. and countries of Western Europe are in sharp contrast with the very strict policies on illegal immigration in the Gulf Cooperation Council (GCC) States and East Asian economies, such as Hong Kong, Singapore, Malaysia, South Korea, Taiwan, and Japan. An illegal immigrant in such states is therefore subject to uncertainty with respect to the duration of stay, while the legal one is not.

Migration of skilled workers is also a highly debated issue. It is recognized that developing countries induce a loss of their highly educated people when the latter decide to move to an advanced economy offering a high wage and a better standard of living. This problem is often referred to in the literature as "brain drain" (see, e.g., Bhagwati and Hamada (1974)). By recruiting skilled professionals from the developing countries, where education is heavily subsidized by the public sector, the advanced countries are widely viewed as pursuing policies detrimental to the source countries.<sup>7</sup> When migration of skilled workers is permanent, the bulk of the potential benefits stemming from public expenditures on training are lost from the perspective of the taxpayers.<sup>8</sup> When it is temporary, there is more scope for gains, especially if the

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<sup>7</sup> It is well recognized that the problem is not only fiscal in nature. The presence of skilled workers in an economy is thought to generate positive externalities at various levels, including technological, social, political and economic. If we take the example of an important sector such as health care, massive emigration of professionals can have a devastating impact on the health status of the population in the short run and a strong negative influence on productivity and welfare in the long run.

<sup>8</sup> Note that even permanent migration can generate benefits for the source country through network effects, by developing business links at home, and through remittance flows. See, e.g., Grubel and Scott (1966), Bhagwati and Hamada (1974), McCulloch and Yellen (1977), Djajić (1986), Lopez and Schiff (1998), Rauch and Casella (2003), Kugler

returnees bring with them productive human capital accumulated while working abroad [see, e.g., Wong (1997), Dustmann (2001), Domingues Dos Santos and Postel-Vinay (2003), Meyr and Peri (2009), Dustmann et al. (2011), and Docquier and Rapoport (forthcoming)].

The vast majority of skilled migrants come from the developing and transition economies with the main poles of attraction being the U.S.A. and Canada, but also the economies of Western Europe [see Lucas (2005)]. Recent efforts to measure the magnitudes of these flows, including the works of Salt (1997), Carrington and Detragiache (1998), Docquier and Marfouk (2006), and Beine et al. (2007), reveal that the brain drain is a particularly acute problem for the relatively small developing countries. In terms of regions, island economies of the Caribbean and the Pacific, as well as countries in Central America, Sub-Saharan Africa, and South-East Asia have the highest skilled-emigration rates in proportion of their skilled populations.<sup>9</sup>

In the 21st century, emigration of skilled workers from the less developed parts of the world continues with a growing number of advanced countries offering fast-track labor-market access for skilled migrants through special temporary visa programs, such as the H1-B visa in the U.S.A. or the “Blue Card” in the EU.<sup>10</sup> In response to a severe shortage of health-care workers, and Rapoport (2007), and Javorcik et al. (2011). In addition, a number of papers examine how the prospect of emigration can contribute to the accumulation of human capital in the source country by inducing individuals to invest more in their education [see, e.g., Mountford (1997), Wong (1997), Stark et al. (1997), Vidal (1998), Beine et al. (2001), Bertoli and Brücker (2011), and Mountford and Rapoport (2011)]. In an important recent study of this relationship, Beine et al. (2008) analyze data for 127 developing economies and find that doubling the emigration rate of the highly skilled induces the population of the source country to increase its human capital formation on the average by 5%.

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<sup>9</sup> See Commander et al. (2004) and Docquier and Rapoport (2008) for very useful surveys of the various issues and evidence related to the brain drain.

<sup>10</sup>In the case of the European Blue Card initiative, highly-skilled non-EU nationals are granted renewable 2 year work permits. In addition, a holder of such a permit, who returns back to his/her country of origin after having worked in the EU for an extended period of time, has the possibility to reenter and work in the EU in the future without going through

Japan has entered into bilateral agreements with Indonesia, the Philippines, and Vietnam to recruit a certain number of nurses on the basis of three-year contracts.<sup>11</sup> Other countries aim to increase their stocks of highly trained workers by means of *permanent* immigration programs. The Canadian points system is a prominent example of this policy, also followed in slightly different forms by Australia, New Zealand and, more recently, Great Britain. In the U.S.A., special permanent residence visas for highly talented individuals have been available for decades.

These practices and policies clearly have an impact on the flows of highly trained migrants from the developing economies. The outflows of skilled workers reduce, in turn, the incentive for the authorities to provide public subsidies for higher education [see Justman and Thisse (1997)]. In an important recent paper, Docquier et al. (2008) examine this question both theoretically and empirically. On the basis of a sample of 108 middle-income and low-income countries they find a negative relationship between education subsidies and skilled emigration rates. An obvious consequence is that the level of training and human capital possessed by the graduates (and thus skilled emigrants) is likely to be lower than it would be otherwise. Lower skills of migrants, in turn, affect the relationship between the costs and benefits of immigration from the perspective of the host countries. This can and does influence their immigration policies. The points systems of Canada, Australia and New Zealand are designed to filter out those with low training and skills. In the U.S.A., whether an H1-B worker can renew her temporary three-year visa depends on the willingness of the employer to sponsor a renewal, which depends to a large extent on the worker's training and ability. This is why it is important

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the application procedure over again (Council Directive 2009/50/EC).

<sup>11</sup>In theory, the foreign nurses can stay longer if they pass a Japanese nursing exam within the three-year period. As fluency in the Japanese language is difficult to achieve for these foreign workers within such a limited period of time, only one Philippino and two Indonesians out of a total of 251 managed to pass the exam in 2010 (see Asahi Shimbun (2010)).

to understand the determinants of the source country's decision to provide public training and host country's decision to hire foreign skilled labor, and highlight the scopes for cooperation and mutual gains. Part I of this dissertation will address this question. It will also discuss two other issues: The difference in saving behavior of legal as opposed to illegal immigrants; and the choice between debt-bonded and self-financed migration. Next subsection will define the research questions addressed in Part II.

## Environmental Preservation

The second broad sets of issues addressed in this dissertation concern with the preservation of the global environment. One of the articles investigates the questions related to optimal investment in an *uncertain* renewable substitute for a non-renewable resource. The other article examines what conditions/policies should be in place in order to induce developing countries to *voluntarily* comply with environmental regulations.

Interest in private and public investment projects devoted to research and development of renewable energy sources ("backstops") is primarily based on concerns about exhaustion of non-renewable energy resources and their ever increasing market price. If we look across countries at the leading investors in energy R&D in per capita terms, we find Japan occupying the first place (IEA 2006). Not surprisingly, this country is also well known for its heavy dependence on energy imports.<sup>12</sup> Within the European Union, the economies leading the way in terms of their share of national income devoted to renewable energy sources are Denmark, Finland, the Netherlands, and Sweden (European Commission 2004). These are again countries that do not possess large stocks of fossil fuels, making them dependent on imports (except for

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<sup>12</sup>Although Japan is only the second largest oil importer after the United States, it meets a larger share of its energy needs through imports of oil than the U.S. does (U.S. Energy Information Administration, <http://www.eia.doe.gov/country/index.cfm>).

the Netherlands which do possess large reserves of natural gas and Denmark, which is expected to continue its North Sea production of oil and gas in excess of its own demand until 2018.)<sup>13</sup>

One of the chapters of this dissertation studies the problem facing a resource-importing country (RIC for short) which seeks to achieve energy independence by developing a substitute for a non-renewable importable input. This is assumed to require sustained investment in an R&D program. Arrival of the substitute follows a stochastic process with the probability of a successful outcome per unit of time being a non-decreasing function of the rate of investment in R&D. Apart from trade in the resource market, RIC can also participate in the global financial market. This latter dimension is most often overlooked in the literature on backstop technology and resource management in general. As we shall see, however, access to international lending and borrowing is important in several dimensions, especially if a country is heavily dependent on imports of an essential input.

The literature on backstop-technology adoption has its origins in the wake of the oil price shock of 1973. The early contributions focus on a *closed* economy, endowed with a known stock of an exhaustible resource, seeking to sustain its consumption in the long run by appropriately substituting a renewable backstop for the non-renewable essential input. The arrival date of the substitute is assumed to be either known with certainty or uncertain but governed by an exogenous stochastic process (see, e.g., Dasgupta and Heal 1974, Dasgupta and Stiglitz 1981). The seminal contribution of Kamien and Schwartz (1978) extends this analysis by endogenizing the uncertain arrival date through investment in R&D. Hung and Quyen (1993) go further to determine the optimal time to initiate the R&D project, although their R&D investment policy is simplified to a single-date expenditure, after which a backstop may arrive with a constant Poisson rate. Tsur and Zemel (2003) propose an alternative (deterministic) framework of analysis, where the cost of

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<sup>13</sup>Denmark is also a major producer and exporter of wind energy (see Sherman (2009)).

the backstop falls continuously as the knowledge base accumulates through R&D. This ensures a continuous transition from the non-renewable to the backstop. Their model advocates an R&D policy characterized by the most rapid approach path to the target-knowledge process which should then be followed forever. The work of Dasgupta, Gilbert and Stiglitz (1983) shows, also in the context of a deterministic model, that the intention to develop a substitute and its eventual arrival can trigger a strategic response from resource owners. Harris and Vickers (1995) study a similar dynamic game, except that the substitute's arrival is random and exponentially distributed.

Although the two latter contributions are concerned with open economies, their analysis is limited to exchange of the resource for the consumption good, while the possibility of international lending and borrowing is ruled out. The trade-theoretic literature, on the other hand, deals with problems related to exhaustible resource management and, in some cases, for countries that have access to foreign credit, but it does not address the problem of optimal investment in the development of a backstop technology.<sup>14</sup> Moreover, these contributions consider purely deterministic models and therefore exclude the possibility of uncertainty affecting behavior.<sup>15</sup> The purpose of the present study is to bridge the existing gap between the closed-economy analysis of investment in a backstop technology and open-economy models of trade in goods and financial assets within a fully dynamic stochastic optimization

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<sup>14</sup>Kemp and Long (1984) do consider resource replacement but in a deterministic setting, where the resource price is exogenous and constant and there is no possibility to participate in the international financial markets. Djajić (1988) considers a two-country world, where both countries are endowed with some stock of the resource and can lend or borrow from each other at an endogenously determined rate of interest. The dynamics of his model are, however, limited to only two time periods and neither country intends to develop a backstop.

<sup>15</sup>An exception is Dasgupta, Eastwood and Heal (1978) who do consider uncertainty related to future energy demand. They also introduce a possibility to accumulate a foreign asset yielding a constant rate of return but focus on a resource-exporting economy, which is not engaged in any R&D activity.

framework. This will make it possible for us to examine the role of international financial markets in influencing optimal investment strategies in a stochastic environment, an issue of increasing importance in a world where energy prices and international indebtedness are becoming dominant themes. This is done in Chapter 5.

Subsequently, Chapter 6 examines what and how policies should be formulated in order to induce developing countries to comply with environmental regulations. There is a global agreement that efforts should be made to deal with climate change. However, there is no unanimous view on how the burden of these efforts should be shared between developed and developing countries. Many advanced countries, and notably the European Union, already have in place various schemes to control their emissions, while none of the developing countries do. The reasons are multiple, including weak environmental policies and legislation, insufficient financing and, most importantly, lower priority attached to issues related to climate change when compared to poverty reduction, standard of living and health improvement, and economic growth.

Given the asymmetry in the climate legislation, some developed countries fear the loss of competitiveness of their energy-intensive industries: A good produced by their domestic firms becomes more expensive as the costs of production rise when emissions permits need to be purchased. European policymakers expressed on several occasions their readiness to apply trade restrictions on countries which do not apply emissions standards similar to theirs. For instance, Manuel Barroso in his interview to *The Times* said: "We do not want to put our energy-intensive industries in a situation of disadvantage in competition terms, that is why we will have measures that we are ready to take if there is not a global climate agreement" (March 2008). Former French president Nicolas Sarkozy said that EU must examine the possibility of "taxing products imported from countries that do not comply with the Kyoto protocol. We have imposed environmental standards on our producers. It is not normal that their competitors should be completely exempted...Environmental dumping is not fair" (October 2007). In particu-



lar, the so-called "border-adjustment measures" were a hot discussion topic and were viewed as indispensable for a climate legislation to pass in the US Congress. "Only sticks" approach, however, may turn out not to be feasible, as it may fail to comply with WTO rules. For example, according to WTO agreement, trade provisions should be preceded by major efforts to negotiate with partners within a reasonable timeframe. Thus, proposed measures may not only include "sticks" but also "carrots", as in the Montreal Protocol (1987) or "clean development mechanism", where trade measures were accompanied by financing arrangements and technology transfers. Developing countries, however, will have to demonstrate a "meaningful" commitment (Zhang 2009), i.e., they are not required to comply with environmental regulations immediately but should take some actions towards compliance at some future date. This is akin to the "grace" period granted to LDCs under the Montreal Protocol.

The effectiveness of "sticks and carrots" policy is yet to be assessed but undoubtedly one cannot do so without first taking the perspective of a less developed country (LDC). Certain conditions must be in place in order for LDC to comply voluntarily with the regulation, otherwise it will not. The purpose of the study is to establish the minimum conditions for voluntary compliance and to analyze the LDC's optimal response to any changes in the conditions it faces. I purposely do not model any restrictive/retaliative measures, such as trade restrictions or environmental taxes, since their acceptable legal format, for example compatible with WTO rules, has not yet been clearly established. By contrast, I focus on supporting/stimulating measures, such as monetary transfers. More specifically, I analyze two types of regulation: One where a predefined transfer is initiated on the date of compliance with emissions target; and the other where the amount transferred is tied to emissions-control effort.

## Thesis Outline and Summary of Results

This dissertation consists of two parts. The first part is devoted to issues related to migration of people across international borders. It consists of three chapters, each addressing a distinct question in the field of international migration. Chapter 2 compares the saving behavior of migrants with legal and illegal status abroad in the context of a dynamic stochastic life-cycle model. The main difference between the two types of migrants is that the former are allowed to stay in the host country for a pre-specified period of time and are obliged to leave when their work permit expires.<sup>16</sup> By contrast, the latter can stay until they are caught by the immigration authorities and subsequently deported. In economies that rely heavily on temporary migration programs, such as the Gulf Cooperation Council (GCC) states, Hong Kong, South Korea, Taiwan, Brunei, and Israel, deportation is a key instrument of immigration control. It also plays an important role in countries such as Japan and Singapore, where the preservation of the existing ethnic structure of the population is an objective of public policy. An illegal immigrant in such states is therefore subject to uncertainty with respect to the duration of stay, while the legal one is not.

The present study is the first to explore the implications of a migrant's legal status for the time path of her propensity to save and for the amount of assets she repatriates to the country of origin. The analysis employs a dynamic stochastic optimization framework in which undocumented immigrants face deportation (arriving with a Poisson rate), while documented migrants

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<sup>16</sup>This is the structure of typical guest-worker programs operated in Taiwan, South Korea, and Singapore, with durations of stay limited to 2 - 5 years. Contract-completion clauses in guest-worker contracts of numerous host economies in Asia allow (in some cases require) employers to withhold a part of a worker's salary until the time of departure. This serves to prevent contract workers from remaining in the host country illegally. The seasonal guest-worker programs in Western Europe and North America typically allow for permits valid for less than a year.

work on a fixed-term contract. The findings contribute to our understanding of how the distinction between "legal" and "illegal" status of migrant workers affects their behavior both at the micro level (as it relates to the optimal consumption and saving) and the macro level (in influencing the average flow of savings per worker back to the source country). Specifically, I show that if the host country's deportation policies are such that an illegal alien faces an expected duration of stay abroad equal to the length of the work permit of a documented guest-worker, the former saves at a *higher* rate than the latter does in the initial phase of their foreign stay. However, should both of them happen to remain abroad for an identical period of time, the former repatriates *less* savings back to the source country than the latter does. While this result may seem counterintuitive at first, it stems from the fact that an undocumented worker's saving rate declines continuously over time, as long as she does not get deported. It quickly falls below the saving rate of a documented migrant after an initial phase of intensive precautionary saving.<sup>17</sup> The model assumes that the Poisson deportation rate is constant. If it were to decrease with the duration of stay abroad (e.g., as a result of learning how to avoid detection), this tendency for the saving rate of an undocumented migrant to decline over time would be even more pronounced.

When comparing *expected* repatriated assets of the two types of migrants, I show that undocumented workers always bring back less savings, on average, than documented workers do, assuming the expected duration of an illegal stay is equal to the duration of the work permit. I also show the combinations of the expected duration of an undocumented stay and the length of a guest-worker contract such that the two types of migrants repatriate, on average, identical amounts of savings. These two immigration policy variables of the host country are shown to have an important influence in determining which type of migration - documented or undocumented - generates a larger per-migrant inflow of foreign exchange into the source country.

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<sup>17</sup>Precautionary saving motive has been studied by, e.g., Skinner (1987), Toche (2005), Wälde (1999), and Zeldes (1989), to mention just a few.

At a more general level, the model helps explain the apparently paradoxical empirical finding that, in spite of the precautionary saving motive, people with relatively more risky incomes save less than people with relatively less risky incomes. As noted by Skinner (1987, p.3): "Empirical comparisons of savings rates among occupations with different income uncertainty provide little support for the view that precautionary savings are important. Data from the 1972-73 Consumer Expenditure Survey imply that self-employed and sales persons, those typically thought to have the most risky income, actually save less than other groups..." The principal finding of the present paper that the precautionary saving phenomenon is short-lived helps explain the paradox and shows that Skinner's observations are perfectly consistent with optimizing behavior.

Chapter 3 investigates the problem facing liquidity-constrained candidates for migration and characterizes the conditions under which they choose debt bondage as the optimal mode of financing their migration costs. This analysis is essential to an informed debate on what factors contribute to the growing incidence of debt-bonded migration and how immigration policies, including border controls and internal enforcement measures of the host countries, affect migration flows. Our objective is to determine how a worker's optimal migration strategy is related to the cost of migration, the conditions in the labor markets at home and abroad, the interest rate charged by the smuggling organization, and the proportion of the migration cost that can be covered by initial liquid asset holdings or borrowing from a family network. We find that debt bondage is the preferred option when the international wage differential is sufficiently large in relation to migration costs. More restrictive border-control measures are shown to reduce the incidence of debt-bonded migration. Depending on the wage gap between the host and source countries, however, such measures may merely induce migrants to switch from debt-bonded to self-financed migration, rather than reduce the total flow of undocumented immigrants. Tougher internal enforcement measures that increase the costs and risks facing employers of bonded laborers are found to

reduce the incidence of debt-bonded migration, increase the incidence of self-financed migration and reduce the overall inflow of undocumented workers. Our model suggests that the reduction in the inflow is likely to be from the relatively poorer of the sending countries.

The possibility of borrowing from family and friends (or financial institutions) on reasonable terms always makes migration more attractive in relation to the "no-migration" option. Under the self-finance arrangement, it enables the migrant to get abroad earlier and earn the high foreign wage over a longer period of time. In the case of bonded migration, a family loan allows the individual to get out of bondage sooner and repay the family loan while earning the free-market wage rather than the bonded wage. Interestingly, with partial financial support from the family, debt bondage becomes more attractive, not only in relation to no migration, but also with respect to self finance. Higher initial asset holdings are found to have similar implications for the optimal migration strategy.

Chapter 4 examines the brain-drain problem within a game-theoretic framework, where both the immigration policy of the host country and the optimal provision of higher education and training in the source country are endogenously determined.

We solve for the Nash equilibrium values of the policy instruments of both countries and examines how they respond to changes in the model's parameters. It is found that the host countries with relatively higher tax rates on income, where the authorities attach a relatively larger weight to employers' interests in their objective function, and where the public sector provides individuals with lower levels of social services, are countries that have stronger incentives to allow their skilled immigrants to work in the economy for a longer period of time. Whether a longer duration of stay raises or lowers the optimal level of training provided by the source country depends primarily on the rate at which immigrants accumulate skills while working abroad and the valuation of those skills after return. It is also found that an increase in the cost of providing public education reduces the equilibrium level of training and

the amount of time immigrants are allowed to work in the host country. An increase in the home-country valuation of skills acquired by migrant workers abroad has the opposite effects on the two policy instruments: The source country provides more training and the host country allows migrants to stay longer. Finally, if the host country chooses to increase its *stock* of immigrants, this will either lower or increase the level of training provided by the source country, depending on the parameters of the model.

If both countries set their policies to maximize joint welfare, the level of training provided by the source country is higher in comparison with its Nash equilibrium value, while the duration of stay of immigrants in the host country may be either higher or lower.

The second Part of this dissertation consists of two chapters. The first, chapter 5, is devoted to the analysis of the optimal investment rate in a renewable substitute for a non-renewable resource under uncertainty. The key results of the paper are the following. Access to international lending and borrowing is shown to allow for a more efficient intertemporal allocation of resources and a higher lifetime welfare as compared with the case of financial autarky. While this is generally to be expected, a comparison of the optimal investment rates under financial autarky and with access to foreign credit enables us to address a number of entirely new issues. First, there is the question of how the degree of dependency on imported energy resources affects the economy's optimal investment in the development of a backstop. On the one hand, greater dependency makes it more urgent to discover a substitute. On the other hand, it also implies a larger import bill prior to invention, which tightens the economy's budget constraint and makes any given investment program relatively more burdensome. My analysis shows that for empirically plausible values of the elasticity of intertemporal consumption substitution, greater dependency on resource imports entails a lower investment rate, with access to foreign credit having a moderating influence.

With access to foreign credit the economy chooses a very different time path of consumption from the one obtained under financial autarky. Due to

the presence of uncertainty, i.e., a possibility of a successful R&D outcome, the economy dissaves during an initial phase of its planning horizon and runs a negative foreign asset position, even when the rate of interest is slightly higher than the rate of time preference. This type of behavior is exactly the opposite of precautionary saving in an environment with negative income shocks (see, e.g., Toche (2005) for the case of a job loss).

When it comes to the optimal choice of the R&D investment rate, having access to capital markets does not necessarily imply that the economy systematically invests more than it does without such access. The outcome depends crucially on the value of the elasticity of intertemporal consumption substitution (EICS). Numerical simulations show, however, that for empirically relevant range of EICS, R&D investment rate with access to credit markets always exceeds the investment rate under financial autarky.

Another key element influencing the optimal choice of the R&D investment rate is the economy's dependence on foreign energy sources, as measured by the share of GDP absorbed by the expenditure on resource imports. In the context of the present model, energy dependence is determined by the market price of the resource and the distributive share of energy in the production of final goods. An increase in the resource price may either boost or decrease the investment rate depending on EICS. The numerical results show that in the empirically relevant range of values for EICS an increase in the resource price leads to a lower optimal investment rate. This result holds regardless of whether or not the economy has access to borrowing and lending. Having access to global capital markets, however, is shown to be equivalent to a reduction in the distributive share of energy resources in production of final goods.

Several interesting results emerge when we look at what role the cost of credit,  $r$ , plays in determining the optimal investment choice and the economy's net foreign asset position (NFA). First, it is shown that, depending on the relationship between  $r$  and the rate of time preference  $\rho$ , RIC may be either a borrower or a lender, and in particular, the lending phase may

precede the phase of borrowing. Second, a successful R&D outcome causes an improvement in the NFA when  $r$  is not too low in relation to  $\rho$  but a *deterioration* in the NFA for low enough interest rates. Third, the economy's expected lifetime welfare with access to credit always exceeds the one obtained under financial autarky, regardless of the value of  $r$ . Moreover, the welfare with access to credit is U-shaped in  $r$  due to the dual role of the latter in the resource and capital markets. Finally, the optimal investment rate responds differently to variations in  $r$  depending on whether access to credit is available or not: it is an increasing function of  $r$  under financial autarky but a *decreasing* function of  $r$  under openness.

The concluding chapter 6 of the thesis studies conditions for compliance with environmental regulations. The main result of the paper is that offering only one regulation type is inefficient. The chances that an LDC complies voluntarily with environmental standards are higher when a menu of options is on the table. The direct implication of this result is that the number and/or diversity of countries willing to comply with environmental standards is also higher when a variety of alternatives is available instead of just one regulation type.



## Part I

# International Migration: Undocumented, Debt-Bonded, and Skilled

## Chapter 2

# Legal and Illegal Immigrants: An Analysis of Optimal Saving Behavior

### 2.1 Introduction

The last couple of decades have witnessed a surge in illegal immigration to the developed countries but also to rapidly growing developing economies in East Asia and elsewhere. The International Organization for Migration estimates that up to one half of migrant workers in developed countries are unauthorized (IOM 2003). Each year, the stock of undocumented migrants in the EU is estimated to be growing by 500'000 individuals (IOM 2004). Inflows of similar magnitude are reported for the U.S.A., with the stock of undocumented immigrants estimated at roughly 10.8 million in the first quarter of 2009 (Center for Immigration Studies 2009). Although illegal immigration is often a source of concern for the receiving economies, it can generate certain benefits for the sending countries, where migrants' remittances and repatriated savings represent important inflows of foreign exchange. According to the World Bank, in El Salvador, Haiti, Jamaica and Jordan, for example, these inflows reached more than 20% of GDP in 2007, while in Tajikistan

they made up as much as 45.5%.<sup>1</sup> In 2008, 192 million foreign workers, including those without proper documentation, sent \$328 billion from developed to developing countries, which is almost triple the amount of official aid flows from OECD member states (World Bank, 2009). Remittances and repatriated savings finance not only everyday consumption but also investment in physical and human capital, thus affecting both directly and indirectly the receiving country's development path.<sup>2</sup> It is therefore important to improve our understanding of the determinants of these flows and hence the saving behavior of migrants who generate them.

In the present study I investigate the saving behavior of temporary foreign workers in the context of a dynamic stochastic life-cycle model, emphasizing the distinction between legal and illegal immigrants. The main difference between the two is that the former are allowed to stay in the host country for a pre-specified period of time and are obliged to leave when their work permit expires.<sup>3</sup> By contrast, the latter can stay until they are caught by the immigration authorities and subsequently deported. In economies that rely heavily on temporary migration programs, such as the Gulf Cooperation Council (GCC) states, Hong Kong, South Korea, Taiwan, Brunei, and Israel, deportation is a key instrument of immigration control. It also plays an important role in countries such as Japan and Singapore, where the preservation of the existing ethnic structure of the population is an objective of

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<sup>1</sup>World Bank <http://blogs.worldbank.org/peplemove/remittance-flows-to-developing-countries>

<sup>2</sup>See Adams (1991), Durand et al. (1996), Lucas (2005), Massey and Parrado (1998), McCormick and Wahba (2001), and Taylor (1987).

<sup>3</sup>This is the structure of typical guest-worker programs operated in Taiwan, South Korea, and Singapore, with durations of stay limited to 2 - 5 years. Contract-completion clauses in guest-worker contracts of numerous host economies in Asia allow (in some cases require) employers to withhold a part of a worker's salary until the time of departure. This serves to prevent contract workers from remaining in the host country illegally. The seasonal guest-worker programs in Western Europe and North America typically allow for permits valid for less than a year.

public policy. An illegal immigrant in such states is therefore subject to uncertainty with respect to the duration of stay, while the legal one is not. I show that this key distinction with respect to the legality of status abroad is responsible for different saving behavior of the two types of migrants. An illegal alien, who is subject to deportation, has an incentive to accumulate "precautionary" savings. While this result is rather intuitive and has already been analyzed in the literature on the optimal saving under uncertainty,<sup>4</sup> the new finding that emerges from my dynamic analysis is that the precautionary motive is short-lived. An undocumented migrant's saving rate falls over time as her expected lifetime earnings are adjusted upwards every day that she avoids apprehension. Moreover, if a legal guest worker and an illegal immigrant face the same expected duration of stay abroad, the latter always repatriates *less* savings back to the home country, provided that both happen to remain abroad for identical periods of time.

This paper builds on two strands of the literature: the one which examines the optimal consumption under uncertainty, on the one hand, and the optimal saving behavior of temporary migrants, on the other hand. The contributions to the first strand typically seek to estimate the share of aggregate savings attributable to income uncertainty (see, e.g., Caballero 1991 and Skinner 1987), while the vast literature on migrants' consumption-saving decisions focuses primarily on the differences between permanent and temporary workers or foreigners and natives,<sup>5</sup> or various factors influencing the optimal saving rate of a temporary foreign worker.<sup>6</sup> None of these studies takes into account a migrant's legal status in the host country, although the legality of status is crucial for optimal decision-making as it determines whether a migrant operates in an uncertain environment or not. The risk of deportation facing illegal

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<sup>4</sup>See, e.g., Skinner (1987), Toche (2005), Wälde (1999), and Zeldes (1989), to mention just a few.

<sup>5</sup>See, e.g., Djajić (1989).

<sup>6</sup>See Djajić (2010), Djajić and Milbourne (1988), Dustmann (1995, 1997), Kirdar (2010), and Mesnard (2004).

immigrants is modeled explicitly by Friebel and Guriev (2006) but their focus is on how it affects the relationship between human smugglers and their clients, rather than on the saving behavior of the latter. The present study is therefore the first to provide a theoretical analysis of the relationship between a migrant's legal status in the host country and her optimal saving behavior.

The remainder of the paper is organized as follows. In Section 2, I solve the optimization problem of a legal guest worker and an undocumented alien. To highlight the role of deportation risk faced by the latter, I structure the problem so as to set aside other factors that affect a migrant's saving rate, such as international commodity-price differentials, interest differentials, location preferences, entrepreneurial opportunities, etc., which have been treated extensively in the aforementioned literature. In Section 3, I compare the saving rates as well as the flows of expected repatriated assets of documented and undocumented foreign workers and discuss how the host country's migration policies affect the source country's inflows of foreign exchange. Finally, I conclude the paper in Section 4 by summarizing its main results.

## 2.2 The Two Types of Migrants

In a very stylized way, I first define the problem facing a documented guest worker and subsequently that of an undocumented immigrant subject to deportation. In both cases I assume that the worker migrates at the beginning of the planning horizon, time  $t = 0$ , and maximizes expected discounted utility of consumption over a lifetime  $T$ .

### 2.2.1 Legal Guest Worker

Consider a migrant who is admitted to work abroad as a legal guest worker (G) on a contract that extends over  $\tau$  units of time. Defining  $c_t$  as her instantaneous consumption rate, G's optimization problem may be written

as

$$\max_{c_t} \int_0^T u(c_t) e^{-\delta t} dt,$$

subject to the budget constraint

$$\int_0^\tau (w^* - c_t) e^{-rt} dt + a_0 + \int_\tau^T (w - c_t) e^{-rt} dt = 0, \quad (2.1)$$

where  $T$  is the length of the planning horizon, and  $\delta$  is the constant rate of time preference. In order to focus on the role of legal status of a worker rather than other factors that may influence saving behavior, I assume that the price levels are equal at home and abroad and normalized to unity. The real wage rates abroad and at home,  $w^*$  and  $w$ , respectively, are assumed constant and  $w^* > w$ . Eq. (2.1) states that the assets accumulated abroad (discounted at the constant risk-free rate of interest,  $r$ , assumed identical in both countries) plus  $a_0$ , the initial asset holdings net of migration cost, must be equal to the discounted excess of consumption over wage income after return.<sup>7</sup> The utility function is assumed to take the iso-elastic form  $u(x) = \frac{x^{1-\theta}}{1-\theta}$ , where  $\frac{1}{\theta}$  is the elasticity of intertemporal consumption substitution (EICS).

G's optimal consumption path satisfies<sup>8</sup>

$$c_t = c_0 e^{\frac{r-\delta}{\theta} t}, \quad c_0 = \left[ w^* \frac{1 - e^{-r\tau}}{r} + a_0 + w \frac{e^{-r\tau} - e^{-rT}}{r} \right] \frac{\frac{r-\delta}{\theta} - r}{e^{(\frac{r-\delta}{\theta} - r)T} - 1}. \quad (2.2)$$

This optimal  $c_t$  reflects the migrant's desire to enjoy a time path of consumption that is smoother than the time path of earnings, consisting of a higher wage abroad and a relatively lower one after return. Defining  $a_t$  as the guest worker's asset position at time  $t$  and  $g \equiv \frac{r-\delta}{\theta} - r$ , we have

$$a_t = a_0 e^{rt} + w^* \frac{e^{rt} - 1}{r} - c_0 \frac{e^{\frac{r-\delta}{\theta} t} - e^{rt}}{g}, \quad a_0 \geq 0, \quad t \in [0, \tau_-], \quad (2.3)$$

$$a_t = a_\tau e^{r(t-\tau)} + w \frac{e^{r(t-\tau)} - 1}{r} - c_\tau \frac{e^{g(t-\tau)} - 1}{g}, \quad a_T = 0, \quad t \in [\tau_+, T] \quad (2.4)$$

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<sup>7</sup>I assume that initial assets are large enough to cover migration costs, i.e.  $a_0 \geq 0$ . I therefore rule out the case of borrowing to finance migration. On this issue see Djajić and Vinogradova (2010).

<sup>8</sup>The derivations of all the equations are relegated to the Appendix.

The amount of assets repatriated at the time of return to the home country is

$$RA^G \equiv a_\tau = \frac{e^{gT} - e^{g\tau}}{e^{gT} - 1} \left[ a_0 e^{r\tau} + w^* \frac{e^{r\tau} - 1}{r} - w \frac{(e^{g\tau} - 1)(1 - e^{r(\tau-T)})}{r(e^{gT} - e^{g\tau})} \right]. \quad (2.5)$$

Later in the paper  $RA^G$  will be compared with the magnitude of savings repatriated by an illegal immigrant. The objective is to see how the saving patterns of the two types of migrants differ and, ultimately, to explain any such differences.

### 2.2.2 Illegal Immigrant

Consider next a migrant who goes abroad as an undocumented alien (U). Assume for simplicity that U and G have the same initial asset holdings net of migration cost and face the same wage rate abroad. The only difference is that due to the illegality of her status, U may be deported back home at any time. The event of deportation is assumed to follow a Poisson process with a constant mean arrival rate  $\lambda$ . If U is caught by the immigration authorities at time  $t$  (with probability  $\lambda dt$ ), she is deported and earns the source-country wage,  $w$ , until the end of her planning horizon without subsequent migration attempts. Alternatively, if U is not caught (with probability  $1 - \lambda dt$ ), she earns the higher host-country wage,  $w^*$ . U's consumption rate while abroad is denoted by  $c_t^u$  and the one after deportation by  $c_t^d$ . The following differential equations describe the evolution of U's asset position over time (by convention, a dot over a variable denotes the derivative with respect to time):

$$\dot{a}_t^u = r a_t^u + w^* - c_t^u, \quad a_0^u \geq 0, \quad (2.6)$$

while U is abroad, and

$$\dot{a}_t^u = r a_t^u + w - c_t^d, \quad a_T^u = 0, \quad (2.7)$$

in the event that U is deported back to the country of origin. The optimal consumption path after deportation can be easily obtained by solving the standard deterministic optimization problem, which is presented in Appendix 2.5.2. The stochastic control problem pertaining to the initial phase (i.e., while U is abroad) is solved with the aid of the Hamilton-Jacobi-Bellman equation and yields the following differential equation for U's consumption rate (see Appendix 2.5.2)

$$\frac{\dot{c}_t^u}{c_t^u} = \frac{1}{\theta} \left\{ \lambda \left[ \left( \frac{c_t^d}{c_t^u} \right)^{-\theta} - 1 \right] + r - \delta \right\}, \quad (2.8)$$

where

$$c_s^d = \left[ a_s^u + \frac{w}{r} (1 - e^{-r(T-s)}) \right] \frac{g}{e^{g(T-s)} - 1} \quad (2.9)$$

if deportation occurs at time  $s$ . Note that if there is no uncertainty, i.e.  $\lambda = 0$ , the first term in the curly braces in eq. (2.8) vanishes and the usual Euler equation for consumption growth rate applies. Furthermore, it is easy to see that the term in the square brackets is unambiguously positive (see Appendix), so that the presence of uncertainty results in a higher consumption growth rate relative to the certainty case. This higher growth rate can be sustained only with a higher saving rate at the beginning of the planning horizon, implying that uncertainty triggers precautionary saving.<sup>9</sup> As will be shown later, however, the precautionary saving is short-lived and the total repatriated assets of U are *lower* than those of G if both end up staying abroad for an identical period of time.

Eqs. (2.8) - (2.9) in combination with the laws of motion of the asset position (2.6) - (2.7) form a system which can be solved (not analytically though) for the optimal paths of  $c_t^u$  and  $a_t^u$ .

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<sup>9</sup>Toche (2005) obtains a similar result in the context of a model with a random employment status. See also Wälde (1999).



## 2.3 Migrants' Saving Behavior

In this Section I numerically solve for U's optimal consumption/saving program. In the next subsection I compare U's saving rate with that of G and illustrate the precautionary saving phenomenon as well as its relatively short duration. I also analyze the evolution of the optimal asset position of the two types of migrants and explain the key finding of the paper: The total repatriated assets of the guest worker always exceed those of the undocumented worker if both happen to remain in the host country for identical periods of time. In the second subsection I discuss the conditions under which the two types of migrants repatriate identical amounts of savings.

The numerical simulations are performed for the following values of the model's parameters. The length of a migrant's planning horizon is assumed to be 30 years to roughly correspond to the remaining working life of an Asian migrant from, say, Thailand, whose average age at the time of migration is reported to be in the early thirties.<sup>10</sup> The length of the guest-worker permit is set at 4 years. In fact, conditions of guest-worker programs vary across host countries. The United States Government Accountability Office (2006, p.26) reports that the duration of a permit may vary from 3 months to 5 years in the countries covered by their study. In Japan, Korea, Hong Kong, and Singapore the permits are typically issued for 2 or 3 years (see, e.g., OECD 2002 and Spencer 1992). OECD (2002) also provides an extensive discussion of immigration policies in Asian countries, including deportation measures aimed at illegal immigrants. For example, in the case of Malaysia, the stock of undocumented Indonesian migrants is estimated to be 450'000 and 10'000 are deported every month (OECD 2002, p.254). These figures imply a deportation rate of 0.26 per year. In Japan, the stock of illegal

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<sup>10</sup>See Jones and Pardthaisong (1999) and Sobieszczyk (2000). Amuedo-Dorantes et al. (2004) report that the average age of Mexican migrants to the U.S. in the Mexican Migration Project (MMP93) was 33 years and their average length of stay was close to 3 years.

aliens was estimated at 193'745 with 33'192 deportations in 2005 (Vogt 2007), implying a deportation rate of roughly 0.17. In line with these figures, the parameter  $\lambda$  is calibrated at 1/4 per year, implying that U's expected stay abroad is equal to 4 years (by the property of the Poisson process). The assumption that U's expected duration of stay abroad is equal to the length of the guest-worker permit will allow us to make meaningful comparisons of their saving behavior: the behavior of G can be interpreted as the certainty-equivalent behavior of U.

An important parameter of the model is  $\theta$ , which is the inverse of the elasticity of intertemporal consumption substitution (hereafter EICS). Although there is not an unanimous view in the literature on the magnitude of this parameter, many empirical studies of EICS conclude that the relevant values lie below 2, which corresponds to  $\theta$  above 0.5.<sup>11</sup> I calibrate  $\theta$  at 0.75 for the benchmark case and check the sensitivity of the results to changes in this parameter. It turns out that even for a wide range of calibrations, from  $\theta = 0.25$  to  $\theta = 5$ , the qualitative conclusions remain unaffected and even the quantitative results are not significantly affected, as we shall see below.

The relative real wage differential is set at 2, which roughly corresponds to the case of Thai migrants in South Korea. The real risk-free interest rate,  $r$ , is 3% per year. The rate of time preference,  $\delta$ , is for simplicity set equal to  $r$ .<sup>12</sup> The parameter values used in the benchmark simulation are summarized in Table 1:

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<sup>11</sup>Vissing-Jørgensen (2002) estimates EICS for stock- and bondholders, distinguishing among 3 wealth groups, as well as for non-stockholders. Her estimates range from 0.29 for stockholders to 1.38 for bondholders with higher estimates for top wealth layer households and close to zero estimates for non-stockholders. See also Epstein and Zin (1991), Hansen and Singleton (1982), and Keane and Wolpin (2001).

<sup>12</sup>With  $\delta = r$  the time path of guest worker's consumption is flat at the level  $c_0$ , while that of the undocumented migrant is upward sloping when she is located abroad and flat after deportation. When  $\delta < r$  ( $\delta > r$ ) the time paths of consumption of both G and U rotate counterclockwise (clockwise), which results in a larger (smaller) amount of savings repatriated to the source country.

planning horizon, years	$T$	30
guest worker permit, years	$\tau$	4
relative real wages	$w^*/w$	2
risk-free interest rate	$r$	0.03
rate of time preference	$\delta$	0.03
Poisson deportation rate	$\lambda$	1/4
elasticity of marginal utility	$\theta$	0.75
initial assets net of migration cost	$a_0$	0

Table 2.1: Benchmark calibration.

### 2.3.1 Comparing Saving Rates

Saving dynamics are illustrated in figure 2.1, with the benchmark case shown by the bold lines. U's time profile of saving (bold dashed line) is drawn under the assumption that deportation occurs precisely at  $t = 4$  (corresponding to the average waiting time until deportation), so that U and G leave the host country simultaneously. The precautionary saving phenomenon can be clearly

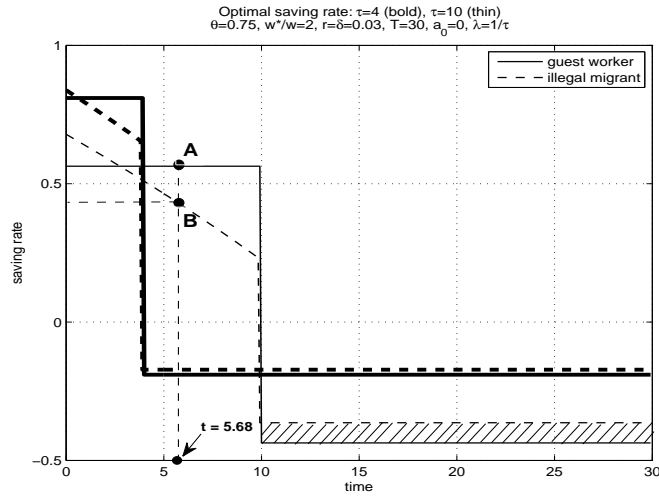


Figure 2.1: Saving rates,  $\tau = 4$  (thick),  $\tau = 10$  (thin).

recognized: U's saving rate exceeds that of G (shown by the bold solid line)

during the first year abroad. Note, however, that U's saving rate declines monotonically until the time of deportation and by then falls well below G's rate, reflecting the higher consumption growth rate under uncertainty derived in eq. (2.8).

What accounts for this lower pace of wealth accumulation in spite of the positive effect of deportation risk on the saving rate in the early phase of U's planning horizon? The apparent paradox can be easily explained. As the time spent abroad by an illegal immigrant increases without detection, her total expected lifetime income continuously grows. She therefore has a weaker and weaker incentive to save, so that her saving rate declines monotonically to fall short of G's rate at the point of return. In fact just prior to being apprehended and deported, U still *expects* to remain in the host country for another  $1/\lambda$  years.

As a comparative statics exercise, I use thin lines in figure 2.1 to show the migrants' saving paths when the deportation policy is less stringent, with  $\lambda = 0.1$ , akin to what we observe, for example, in the EU. To have a meaningful comparison,  $\tau$  is set at  $1/\lambda = 10$ . The corresponding saving schedules follow exactly the same pattern as in the benchmark case, except for the downward displacement. The saving rate abroad is reduced for both U and G as their expected duration of stay (and therefore their lifetime earnings) are increased. Also note that U's dissaving rate after return is lower than that of G since U has not accumulated as much wealth abroad as G has. The discrepancy is more pronounced for lower Poisson deportation rates.

Differences in the saving rates of U and G translate into different time paths of their asset positions. Figure 2.2 shows the evolution of asset holdings of U (dashed line) and of G (solid line) for the case of  $\tau = 10$  and  $\lambda = 0.1$ . The precautionary saving phenomenon can be recognized again by noting that the undocumented migrant's asset position exceeds that of the guest worker until approximately  $t = 5.68$ . Recall that the growth rate of a migrant's asset position is just the interest earned on the stock of assets plus the saving rate. At time  $t = 5.68$  the asset positions of G and U are equalized but the saving

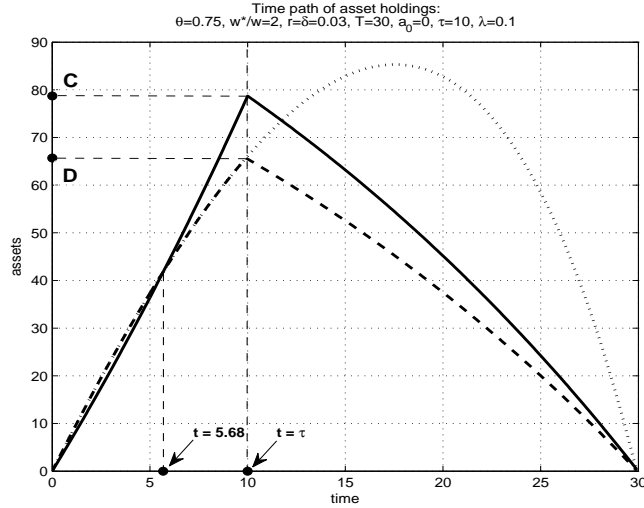


Figure 2.2: Total assets.

rate of  $U$  is lower than that of  $G$  by the amount  $AB$  in figure 2.1, so that the growth rate of  $U$ 's asset position (the slope of the dashed line in figure 2.2) is lower than the growth rate of  $G$ 's asset position (the slope of the solid line). By the time of deportation at  $t = 10$ ,  $U$ 's asset holdings are 16.55% lower than those of  $G$ . The difference in repatriated wealth, shown by the distance  $CD$ , corresponds to the shaded surface in figure 2.1. Should  $U$  be lucky enough to never get deported, her stock of assets would evolve along the dotted line.

The saving rates, and consequently the magnitude of accumulated assets, depend on the chosen value of the elasticity of intertemporal consumption substitution (EICS). In the next figure I show, however, that EICS plays a minor role, in the sense that none of the qualitative results concerning the saving rates are affected by a large change in EICS. Moreover, even the quantitative results are not significantly affected.<sup>13</sup> Figure 2.3 shows the saving

<sup>13</sup>As noted earlier, in order to focus on the implications of deportation risk on saving behavior, I have assumed that commodity prices and interest rates are identical across countries. What makes saving rates highly sensitive to changes in  $\theta$  in other models of temporary migration are price level and interest rate differentials which trigger intertemporal substitution of source-country for host-country consumption (e.g., Djajić 2010).

dynamics of  $U$  and  $G$  for the benchmark case  $\theta = 0.75$  (EICS=1/ $\theta$ =1.33) with bold lines, while the thin lines show  $U$ 's saving rate for  $\theta = 0.25$  (bottom line),  $\theta = 1.75$  (thin dashed line), and  $\theta = 5$  (thin solid line).

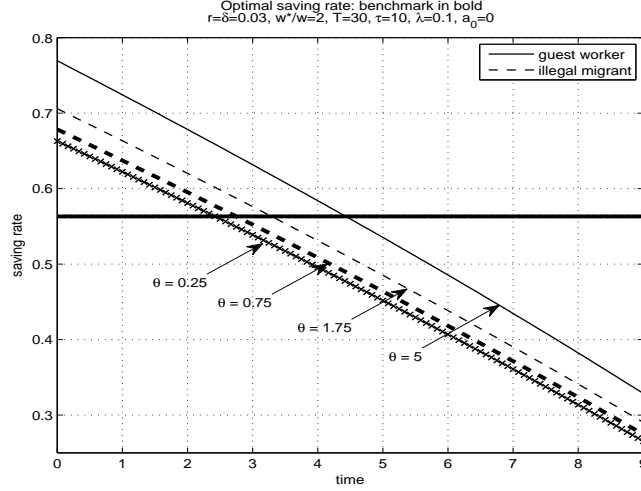


Figure 2.3: Saving rates and EICS: benchmark  $\theta = 0.75$  (bold),  $\theta = 0.25$  (bottom),  $\theta = 1.75$  (thin dashed),  $\theta = 5$  (thin solid).

The simplifying assumption that  $r = \delta$  implies that  $\theta$  does not affect the optimal consumption path of  $G$  (see eq. (2.2)) but it does affect the optimal consumption path of  $U$  (recall eq. (2.8)) and consequently the position of the dashed line. Figure 2.3 demonstrates that the difference between  $U$ 's saving rate under alternative calibrations of  $\theta$  is quite small with a slightly higher saving rate associated with a greater degree of concavity of the utility function. For instance, at the moment just before deportation ( $t = 10$ )  $U$  saves 11.61% of her income with  $\theta = 0.75$  and 12.35% of her income with  $\theta = 1.75$ . The repatriated assets are only 4.55% higher with a higher  $\theta$  and are still 12.74% below those of  $G$ .

The assumption that deportation of  $U$  occurs precisely on the date that coincides with the expiration of the work permit for  $G$  is a useful expositional tool that enables us to highlight the differences between saving behavior of the two types of migrants under specific conditions. In reality, deportation may

occur at any time and, in addition, there is no reason to expect that a host country's choice of  $\tau$  is identical to its choice of  $1/\lambda$ . In the next subsection I consider the general case where the focus of the analysis is on the determinants of the *aggregate* flows of repatriated assets that a source country can expect to receive for any given stock of migrants employed abroad.

### 2.3.2 Comparing Repatriated Assets

As noted in the Introduction, repatriated savings of temporary migrants play a very important role at the macroeconomic level in the countries of emigration. Tens of billions of dollars flow every year back to countries like China, India, Mexico, and the Philippines. For less populous labor-exporting countries, the dollar figures are more modest, but in many instances constitute a large percentage of GDP.<sup>14</sup> Much of these flows stem from the savings of undocumented migrant workers. Center for Immigration Studies (2007) estimates that 55% of all Mexican migrants residing in the U.S.A. are illegal. For Central Americans the figure is 47% and for South Americans 33%. In light of these numbers, my analysis of the optimizing behavior of U and G naturally raises some important questions that have not been addressed in the theoretical literature: Does a larger proportion of documented to undocumented migrants contribute to a larger or smaller inflow of repatriated savings per worker? How is this relationship affected by the host country's deportation policy and its restrictions on the maximum duration of a guest-worker contract? In the analysis that follows I develop a basis for addressing these questions by first comparing the magnitude of repatriated assets of a guest worker,  $RA^G$ , with the *expected* repatriated assets of an illegal immigrant,  $ERA^U$ .<sup>15</sup>

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<sup>14</sup>For example, in 2009 remittances and repatriated assets represented 22.4% of GDP in Moldova and 35.11% in Tajikistan (The World Bank Data).

<sup>15</sup>Since G does not face any uncertainty with respect to her duration of stay abroad, her actual and expected RA are identical. Due to the risk of deportation, however, those of U

The amount that a guest worker repatriates at the point of return is given by eq. (2.5). In the case of an undocumented migrant, the expected amount of repatriated assets is defined as  $ERA^U = \int_0^T a_s f_s ds$ , where  $f_s = \frac{\lambda e^{-\lambda s}}{1 - e^{-\lambda T}}$  is the density of a truncated-exponentially distributed random variable.<sup>16</sup> Figure 2.4 shows  $ERA^U$  (dashed line) and  $RA^G$  (solid line) as functions of the (expected) duration of stay abroad:  $1/\lambda$  for U and  $\tau$  for G. For instance, point  $C$  in figure 4 corresponds to point  $C$  in figure 2.2.

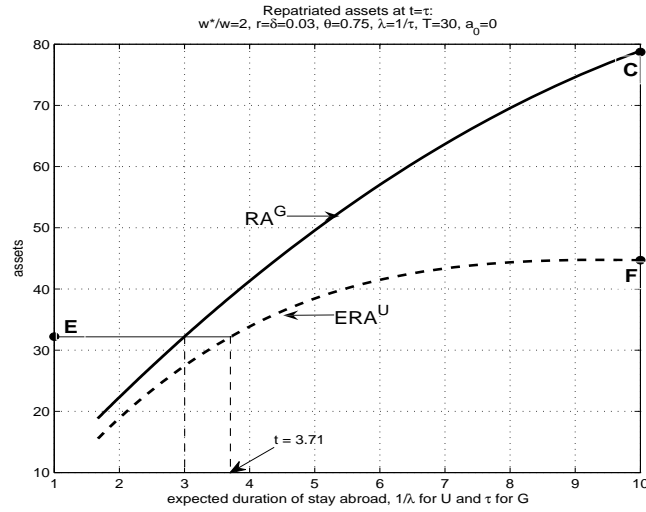


Figure 2.4: Expected repatriated assets.

The value of assets corresponding to point  $F$  in figure 4 is, however, the *average* flow of repatriated assets per deported undocumented worker when  $\lambda = 0.1$ . It is lower than that marked by  $D$  in figure 2.2, which is the amount of assets that a deportee repatriates under the assumption that  $\lambda = 0.1$  and that deportation occurs precisely at  $t = 1/\lambda$ .

Considering realistic durations of stay abroad, figure 2.4 demonstrates that, on average, the savings brought back by a deported undocumented

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<sup>16</sup>Given that the event of deportation follows the Poisson process, the waiting time until deportation is an exponentially-distributed random variable. The truncation is necessary since the migrant's planning horizon is finite (equal to  $T$ ). With an infinite horizon, the density is just the numerator of  $f_s$ .



worker are always lower than those of a documented one if the deportation policy is such that  $\lambda = 1/\tau$ .<sup>17</sup> For the benchmark values of the model parameters, an average undocumented migrant repatriates 14.83% less than a documented worker when the expected duration of stay abroad for both types of workers amounts to 3 years. This percentage increases monotonically with the expected duration of stay, reaching 43.37% when the duration is 10 years. Thus, an average undocumented deportee will bring back the same amount of savings as a documented guest worker only if  $\lambda < 1/\tau$ . In particular, if  $\tau$  is set at three years, as is often the case, for example, in South Korea, Singapore and Taiwan, an undocumented immigrant earning the same wage as a documented guest worker will repatriate an identical amount of savings (shown by point *E* in figure 2.4) only if her expected duration of stay abroad is 3.71 years.

This analysis of the links between immigration policies of a host country and the migrants' saving behavior can be extended further to identify combinations of the maximum contract duration ( $\tau$ ) and the deportation rate ( $\lambda$ ) such that the two types of migrants bring back identical amounts of expected repatriated assets. These combinations are traced by the hump-shaped curve in figure 2.5, showing the values of  $\tau$  (on the vertical axis) and  $1/\lambda$  (on the horizontal axis) such that  $RA^G = ERA^U$ . Anywhere above (below) the curve, G repatriates more (less) assets than U does. Note that the  $RA^G = ERA^U$  schedule lies to the right of the 45-degree line, confirming what has been established in figure 2.4: For any expected duration of an illegal stay abroad, which is equal to (or less than) the maximum duration of a guest-worker permit, U repatriates less assets, on average, than G does.

For realistic expected durations of undocumented stay, which are arguably

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<sup>17</sup>For very high expected durations of stay abroad ( $\lambda \rightarrow 1/T$ ) and the corresponding lengths of the permit ( $\tau \rightarrow T$ ), G behaves as a permanent migrant and her repatriated savings are then approaching zero, while U's expected RA are positive due to the presence of deportation risk. These values of  $\tau$  are, however, far beyond realistic values and therefore ruled out from the rest of the analysis.

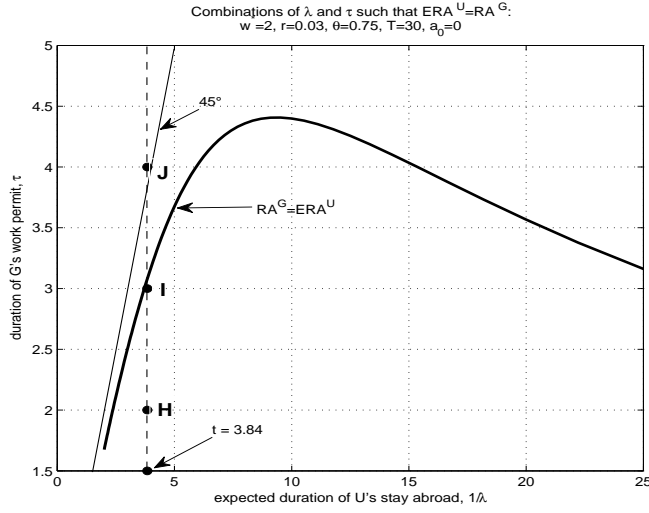


Figure 2.5: Combinations of  $\tau$  and  $\lambda$  such that  $ERA^U = RA^G$ .

to the left of the peak of the curve, one can identify which migrant type contributes more to the aggregate inflow of foreign exchange from a given host country. For instance, undocumented Indonesian migrants in Malaysia face a deportation rate of 0.26 or their expected length of stay is 3.84 years. If an Indonesian guest worker is allowed to work in Malaysia for only 2 years (point  $H$  in figure 2.5), he will repatriate less assets than an undocumented worker; if allowed to work for 3 years (point  $I$ ), the two types of migrants will repatriate almost identical amounts; while if the contract is for 4 years (point  $J$ ),  $G$ 's repatriated savings will exceed those of  $U$ . Accordingly, if Malaysia's immigration policies correspond to point  $H$  (point  $J$ ), the model predicts that an increase in the proportion of undocumented to documented Indonesian migrants will result in an increase (decrease) in Indonesia's inflow of repatriated savings per migrant worker.

As a final point, note that an increase in the foreign wage rate,  $w^*$ , shifts the  $RA^G = ERA^U$  schedule up. Thus the greater the international wage differential, the greater the value of  $ERA^U$  relative to  $RA^G$ . Figure 2.6 shows the  $RA^G = ERA^U$  schedule for  $w^* = 2$  (benchmark case),  $w^* = 4$ , and  $w^* = 6$ , with the source-country wage,  $w$ , normalized to unity. The main

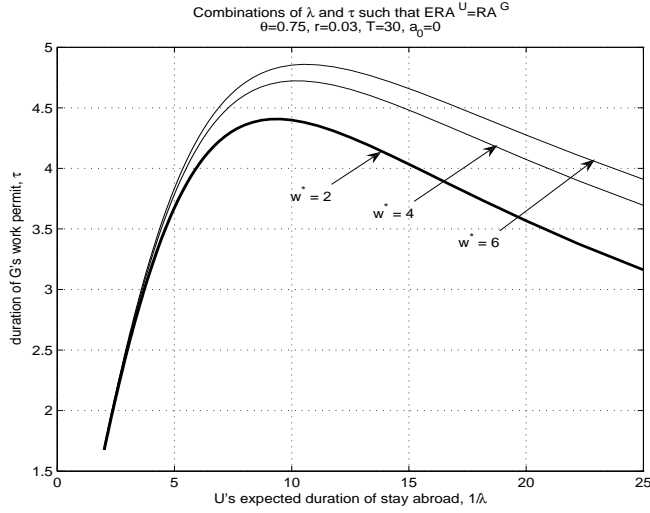


Figure 2.6: Effect of change in foreign wage.

message conveyed by the figure is that changes in  $w^*$  do not have a large quantitative impact on  $RA^G$  relative to  $ERA^U$  for empirically relevant values of the immigration policy parameters  $\tau$  and  $\lambda$ . This is particularly true in the East Asian context where deportation measures are quite strict and guest-worker contracts limited in duration to just a few years.

## 2.4 Conclusion

The present study is the first to explore the implications of a migrant's legal status for the time path of her propensity to save and for the amount of assets she repatriates to the country of origin. The analysis employs a dynamic stochastic optimization framework in which undocumented immigrants face deportation (arriving with a Poisson rate), while documented migrants work on a fixed-term contract. The findings contribute to our understanding of how the distinction between "legal" and "illegal" status of migrant workers affects their behavior both at the micro level (as it relates to the optimal consumption and saving) and the macro level (in influencing the average flow

of savings per worker back to the source country). Specifically, I show that if the host country's deportation policies are such that an illegal alien faces an expected duration of stay abroad equal to the length of the work permit of a documented guest-worker, the former saves at a *higher* rate than the latter does in the initial phase of their foreign stay. However, should both of them happen to remain abroad for an identical period of time, the former repatriates *less* savings back to the source country than the latter does. While this result may seem counterintuitive at first, it stems from the fact that an undocumented worker's saving rate declines continuously over time, as long as she does not get deported. It quickly falls below the saving rate of a documented migrant after an initial phase of intensive precautionary saving. The model assumes that the Poisson deportation rate is constant. If it were to decrease with the duration of stay abroad (e.g., as a result of learning how to avoid detection), this tendency for the saving rate of an undocumented migrant to decline over time would be even more pronounced.

When comparing *expected* repatriated assets of the two types of migrants, I show that undocumented workers always bring back less savings, on average, than documented workers do, assuming the expected duration of an illegal stay is equal to the duration of the work permit. I also show the combinations of the expected duration of an undocumented stay and the length of a guest-worker contract such that the two types of migrants repatriate, on average, identical amounts of savings. These two immigration policy variables of the host country are shown to have an important influence in determining which type of migration - documented or undocumented - generates a larger per-migrant inflow of foreign exchange into the source country.

At a more general level, the model helps explain the apparently paradoxical empirical finding that, in spite of the precautionary saving motive, people with relatively more risky incomes save less than people with relatively less risky incomes. As noted by Skinner (1987, p.3): "Empirical comparisons of savings rates among occupations with different income uncertainty provide little support for the view that precautionary savings are important. Data

from the 1972-73 Consumer Expenditure Survey imply that self-employed and sales persons, those typically thought to have the most risky income, actually save less than other groups..." The principal finding of the present paper that the precautionary saving phenomenon is short-lived helps explain the paradox and shows that Skinner's observations are perfectly consistent with optimizing behavior.

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## 2.5 Appendix

### 2.5.1 Legal Guest Worker

The objective is to maximize

$$V^G = \int_0^T u(c_t)e^{-\delta t} dt,$$

subject to the budget constraint

$$\int_0^\tau (w^* - c_t)e^{-rt} dt + a_0 + \int_\tau^T (w - c_t)e^{-rt} dt = 0. \quad (2.10)$$

The Lagrangian function is given by

$$L = \int_0^T u(c_t)e^{-\delta t} dt + \mu \left[ \int_0^\tau (w^* - c_t)e^{-rt} dt + a_0 + \int_\tau^T (w - c_t)e^{-rt} dt \right]$$

and the first order condition with respect to consumption choice

$$\frac{\partial L}{\partial c_t} = u'(c_t)e^{-\delta t} - \mu e^{-rt} = 0. \quad (2.11)$$

Eq. (6.5) implies that consumption rate is equal to  $c_t = c_0 e^{\frac{r-\delta}{\theta}t}$ , with  $c_0 = \mu^{-1/\theta}$  and where we used the iso-elastic utility specification  $u(x) = \frac{x^{1-\theta}}{1-\theta}$ .

Using this in the budget constraint (2.10) we obtain

$$\int_0^\tau (w^* - c_0 e^{\frac{r-\delta}{\theta}t})e^{-rt} dt + a_0 + \int_\tau^T (w - c_0 e^{\frac{r-\delta}{\theta}t})e^{-rt} dt = 0.$$

Solving for  $c_0$ , we obtain eq. (2) in the text.

### 2.5.2 Illegal Immigrant

The problem of a migrant facing a risk of deportation is a stochastic optimal control problem which can be addressed by writing the Hamilton-Jacobi-Bellman equation

$$Max \quad \left\{ u(c_t^u) + \frac{\partial V_t}{\partial a_t} (ra_t + w^* - c_t^u) \right\} + \lambda(V_t^d - V_t) - \delta V_t = 0, \quad (2.12)$$

where the superscript  $d$  stands for "deportation" and  $V_t$  is U's value function. The first order conditions with respect to  $c_t^u$  and  $a_t$  yield

$$u'(c_t^u) - \frac{\partial V_t}{\partial a_t} = 0, \quad (2.13)$$

$$\frac{\partial^2 V_t}{\partial a_t^2} \dot{a}_t + r \frac{\partial V_t}{\partial a_t} + \lambda \left( \frac{\partial V_t^d}{\partial a_t} - \frac{\partial V_t}{\partial a_t} \right) - \delta \frac{\partial V_t}{\partial a_t} = 0. \quad (2.14)$$

Differentiating (2.13) with respect to time and using the result in (2.14) yields

$$\frac{u''(c_t^u)}{u'(c_t^u)} \dot{c}_t^u + r + \lambda \left( \frac{u'(c_t^d)}{u'(c_t^u)} - 1 \right) - \delta = 0.$$

After rearranging terms and using  $u'(c_t^i) = (c_t^i)^{-\theta}$  ( $i = d, u$ ) we obtain

$$\frac{\dot{c}_t^u}{c_t^u} = \frac{1}{\theta} \left\{ \lambda \left[ \left( \frac{c_t^d}{c_t^u} \right)^{-\theta} - 1 \right] + r - \delta \right\}. \quad (2.15)$$

Note that the term in the square brackets is unambiguously positive as the consumption rate in deportation,  $c_t^d$ , is always smaller than  $c_t^u$ , otherwise migration would not have taken place. Thus the ratio  $c_t^d/c_t^u$  raised to a negative power is always greater than unity.

It is obvious from the above equation that the solution depends on the migrant's consumption in "deportation",  $c_t^d$ . But  $c_t^d$  can be easily obtained by solving the deterministic optimization problem of an individual who is deported at an arbitrary time, say  $\xi \in [0, T]$ . His objective is to maximize

$$\int_{\xi}^T u(c_t^d) e^{-\delta(t-\xi)} dt$$

subject to

$$\dot{a}_t = r a_t + w - c_t^d, \quad (2.16)$$

the terminal condition  $a_T = 0$  and the initial condition given by  $a_{\xi}$ , i.e. the amount of assets accumulated abroad up to time  $\xi$  which the migrant brings with him to the source country at the time of deportation.

The present value Hamiltonian is

$$H = u(c_t^d) e^{-\delta(t-\xi)} + \nu_t [r a_t + w - c_t^d],$$

where  $\nu_t$  is the co-state variable, and the first order conditions are

$$\frac{\partial H}{\partial c_t^d} = 0 \Rightarrow u'(c_t^d)e^{-\delta(t-\xi)} = \nu_t \quad (2.17)$$

$$\frac{\partial H}{\partial a_t} = -\dot{\nu}_t \Rightarrow r\nu_t = -\dot{\nu}_t \quad (2.18)$$

Taking the time derivative of (2.17) and using the result in (5.4) we obtain the usual Ramsey type condition for consumption growth rate

$$\frac{\dot{c}_t^d}{c_t^d} = \frac{r - \delta}{\theta}, \quad t \in [\xi_+, T].$$

This equation implies the following consumption path

$$c_t^d = c_\xi^d e^{\frac{r-\delta}{\theta}(t-\xi)},$$

where  $c_\xi^d$  is determined by solving the differential equation for asset accumulation (2.16):

$$c_\xi^d = \left[ a_\xi + \frac{w}{r} (1 - e^{-r(T-\xi)}) \right] \frac{g}{e^{g(T-\xi)} - 1}, \quad (2.19)$$

Now eq. (2.19) can be substituted in (2.15) to yield the law of motion for the illegal immigrant's consumption. The next step is to solve the system of two differential equations, one for consumption and the other for assets accumulation, which is done numerically.

## Chapter 3

# Liquidity-Constrained Migrants\*

### 3.1 Introduction

In an effort to control immigration over the last couple of decades, the advanced countries have introduced new barriers to international mobility of low-skilled workers. With the increasing complexity of overcoming these barriers, migrants are relying more and more on the services of human smuggling organizations to help them reach their desired destination. As reported by Petros (2005), the fees for smuggling services vary depending on the distance traveled, the means of transport, and the entry strategy. They range from hundreds of dollars for an assisted crossing of a single border to tens of thousands of dollars on certain long-haul routes. Although the amounts paid to smugglers may not be very large in relation to the expected income abroad, from the perspective of low-skilled workers in the poor developing countries, the cost of migration represents a big obstacle that stands in the way of their migration plans.<sup>1</sup>

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<sup>1</sup>There is a growing empirical literature that offers evidence on the effects of liquidity constraints on international migration. Angelucci (2004) uses data from the Progres program in Mexico to study the impact of transfers to liquidity-constrained, rural households on both internal and international migration. She finds that unconditional cash transfers

A key question is how to pay for the cost of migration. One possibility is to accumulate enough savings out of income earned in the source country. We would expect this "self-finance" solution to be attractive when the cost of migration is low in relation to the source-country wage. When the cost is in the tens of thousands of dollars, as in the case of undocumented migration from China to Western Europe and North America, there may be no scope for accumulating the required amount out of the income earned at home. In such cases it would be necessary to borrow in order to migrate.

Borrowing can take place from a network of family and friends, part of which may already be located in the host country, or by getting indebted to a human smuggling organization. When borrowing from relatives or friends, the loan agreement is typically informal, with the interest obligations (if any) and the contract-enforcement mechanism varying from one culture to another. By contrast, when a migrant borrows from a smuggling organization, enforcement is very strict and the rates of interest are often 30% or even 60% per annum.<sup>2</sup> These rates reflect not only the high degree of risk incurred by the lender but also the high transactions and enforcement costs. As a way of controlling these costs, the smuggler typically obliges the migrant to become a bonded laborer with (a partner of) the smuggling organization until the loan is paid off. While in bondage, the migrant's freedom of movement is limited and the wage earned is usually lower than the free-market wage in the host country.<sup>3</sup>

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are associated with a 60% increase in the average migration rate, while the likelihood of having migrants in the household is a positive function of the amount received through the program. In the case of El Salvador, Halliday (2006) reports that higher household wealth is positively associated with migration to the U.S.A. For internal migration in Russia, Andrienko and Guriev (2004) find evidence that inter-regional migration is constrained by lack of liquidity and that it rises with an increase in income. All these studies point to the importance of liquidity constraints in restricting contemporary international migration, confirming what we already know about the role of such constraints in the 18th and 19th centuries (see, e.g., Hatton and Williamson (1992, p.7) and Chiswick and Hatton (2006, p.2)). See also Grubb (1985), Galenson (1984), and Hatton and Williamson (1994, 1998).

<sup>2</sup> See Kwong (1997, p.38), Gao (2004, p.11) and Sobieszcyk (2000, p.412).

<sup>3</sup> According to the US State Department, indentured migrants were put to work "...at

To many observers, debt-bonded migration involves gross violations of human rights and corresponds to a modern-day form of slavery. As its incidence has grown over the last couple of decades, it has attracted an increasing amount of attention in policy circles, both at the national and multilateral levels, with the aim of curbing this form of international labor mobility.<sup>4</sup> The purpose of the present study is to characterize the conditions under which candidates for migration choose debt bondage as the optimal mode of financing their migration costs. This analysis is essential to an informed debate on what factors contribute to the growing incidence of debt-bonded migration and how immigration policies, including border controls and internal enforcement measures of the host countries, can help deter it. The scope of our study is limited to voluntary debt-bondage contracts, which are entered into on the basis of more or less perfect information.<sup>5</sup> An analysis of human trafficking, which involves deception, strategic behavior, coercion, kidnapping, and violence, is beyond the scope of our paper.<sup>6</sup>

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lower than minimum wage and used most of their savings to pay down their debt at usurious interest rates." [United States Department of State (2006)]. See Gao and Poisson (2005), Human Rights Watch (2000), Kwong (1997), Salt (2000), Sobieszczyk (2000), Stein (2003), Surtees (2003), and Vayrynen (2003) for informative discussions of the conditions facing migrants in debt bondage.

<sup>4</sup> See Andrees (2008), Human Rights Watch (2000), and United States Department of State (2006). The Palermo Protocols, adopted by the United Nations in 2000, address the problems of migrant smuggling and human trafficking. Although they draw a distinction between human trafficking and smuggling through the element of exploitation, deception and coercion, Andrees (2008, p.13) notes that, with respect to debt-bonded migration, "The lack of viable economic alternatives that makes people stay in an exploitative work relationship... may constitute a position of vulnerability as defined by the Palermo Protocol."

<sup>5</sup>In light of some media reports on the experience of illegal immigrants, it may seem odd that we should think of human smuggling and debt-bonded migration in the context of a perfect-information framework. As we shall see below, whether such a framework is a reasonable approximation depends largely on the characteristics of the market and the role of a smuggler's reputation in enabling him to attract new clients.

<sup>6</sup>The problem of trafficking is analyzed from a theoretical perspective by Tamura (2010).

The present study is not the first to analyze the role of liquidity constraints in a model of international migration. A paper by Friebe and Guriev (2006) models explicitly the interaction between wealth-constrained migrants and smugglers, with a focus on the conditions under which the latter are willing to offer credit to the former. They confine their analysis, as we do, to voluntary debt-bondage arrangements and provide a number of important new findings on the effectiveness of border controls and deportation measures in deterring illegal immigration of liquidity-constrained individuals. Friebe and Guriev (2006), however, do not explicitly model saving behavior. Their candidates for migration are endowed with a certain initial stock of assets, which can be either greater or smaller than the cost of migration. If it is smaller, they can migrate only as bonded laborers. By contrast, the focus of the present study is on the optimizing behavior of liquidity-constrained individuals, including their saving behavior. This opens up a wider range of options for a potential migrant, both with respect to the mode of financing and the optimal timing of departure from the source country.

Our objective is to determine how a worker's optimal migration strategy is related to the cost of migration, the conditions in the labor markets at home and abroad, the interest rate charged by the smuggling organization, and the proportion of the migration cost that can be covered by initial liquid asset holdings or borrowing from a family network. We find that debt bondage is the preferred option when the international wage differential is sufficiently large in relation to migration costs. More restrictive border-control measures are shown to reduce the incidence of debt-bonded migration. Depending on the wage gap between the host and source countries, however, such

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He examines the equilibrium degree of migrant exploitation by the smugglers in a model where the migrants are not liquidity constrained, but have enough personal savings to pay the smuggling fee on arrival at the destination. A recent empirical study by Mahmoud and Trebesch (2010) examines the factors that influence the incidence of trafficking within a migrant population. This work, as well, does not touch on the issue of migrant indebtedness or whether the debt is owed to a smuggling organization or family and friends.



measures may merely induce migrants to switch from debt-bonded to self-financed migration, rather than reduce the total flow of undocumented immigrants. Tougher internal enforcement measures that increase the costs and risks facing employers of bonded laborers are found to reduce the incidence of debt-bonded migration, increase the incidence of self-financed migration and reduce the overall inflow of undocumented workers. Our model suggests that the reduction in the inflow is likely to be from the relatively poorer of the sending countries.

The remainder of the paper is organized as follows. Section 2 describes the market for human smuggling and defines the migrant's optimization problem in the debt-bondage and self-finance scenarios. Section 3 compares the utility of remaining at home with the utilities of migrating under these two alternative financing schemes and characterizes the conditions under which one or the other is more attractive. Section 4 introduces the possibility of borrowing from a family network in order to cover a part of migration costs. The links between our model and some stylized facts are discussed in Section 5. Finally, Section 6 concludes the paper by summarizing its main results.

## 3.2 Self-Financed vs Debt-Bonded Migration

We compare two alternative ways of paying for migration costs: By accumulating savings out of source-country income (self-financed migration) and by borrowing from a smuggler with a commitment to repay the loan out of income earned in the destination country (debt-bonded migration). Either way, once the migration cost is paid, we assume that the smuggling organization guarantees passage to the destination.<sup>7</sup>

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<sup>7</sup>This is usually the case in the Chinese market for human smuggling. The client is initially required to make a fractional down payment. If a smuggling attempt is unsuccessful, the contract calls on the smuggling organization to try again to bring the client to the destination. Full payment for smuggling services is made only after the client arrives safely at the destination.

Human smuggling operations take many different shapes and forms. Some are run by genuine travel agents, who gradually entered the smuggling business in the process of trying to help their clients realize their travel plans without proper documentation. Enterprizes of this type can be found, for example, throughout South, South-East, and East Asia. They charge a fee for providing business or academic credentials, letters of invitation, false or modified stolen passport, and other documentation needed for travel to the desired destination. They seem to operate competitively in areas where their customers live, their track record is well known in the community, and they depend very much on their reputation in attracting new clients. Smuggling of Chinese undocumented migrants into Western Europe and North America has similar features in that the reputation of the service provider is a key asset. This limits the scope for client abuse and opportunistic behavior on the part of the smugglers.<sup>8</sup>

By contrast, the situation is very different in the market for human smuggling in the Balkans, North Africa, and Turkey. In those cases migrants from distant countries, poorly informed, and eager to get to their final destination, end up involved in arrangements with opportunistic smugglers who are in fact exploitative criminals. In such markets, where a solid reputation of the service provider is not essential for getting new clients, because poorly informed migrants arrive spontaneously to the market to be matched almost at random with the smugglers, transport services and criminal abuse are often parts of a single package, as analyzed very carefully and discussed in papers by Tamura

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<sup>8</sup>Chin (1999) reports on the basis of his New York survey that smuggled Chinese nationals often considered their smugglers (or "snakeheads") as philanthropists. Another survey based on 129 interviews with snakeheads in New York City, Los Angeles, and Fuzhou, conducted by Zhang and Chin (2002), provides details on the structure of Chinese human-smuggling operations into the United States and on the relationship between the smugglers and their clients. There is a clear sense that the smugglers are genuinely concerned about the responsibilities to their clients. See Djajić and Vinogradova (2012) for further discussion.

(2010, 2011).<sup>9</sup> Better informed or more experienced migrants fare better in these markets than the ones who are not (see Gathmann (2008)). Following Friebel and Guriev (2006), however, we focus on purely human-smuggling activities that do not involve exploitation of clients through strategic behavior, deception, and physical abuse. A competitive smuggling organization offers the migrant a contract and honors it in full.<sup>10</sup> This is the type of framework that we consider in the present study.

The advantage of self-financed in relation to debt-bonded migration in this setting is not having to pay excessive interest charges and not being subjected to the constraints of bondage on arrival in the host country. The advantage of debt-bondage is that it allows the migrant to reach the host country sooner. This means being able to sell his labor services at a wage higher than that of the source country, although the bonded wage may be lower than the free-market wage at the destination.

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<sup>9</sup>Similar conditions prevail in the markets for human smuggling services along the US-Mexico border. Migrants arrive there after a long journey from the interior of Mexico or yet another country and often lack knowledge of the market conditions or service providers. There is considerable scope then for rent extraction through strategic behavior on the part of smugglers, who may be heterogeneous in terms of their capacity to exploit clients (see Tamura (2011) and the related papers on migrant smuggling by Auriol and Mesnard (2012) and Halliday and de Paula (2011)).

<sup>10</sup>This type of relatively orderly arrangement in an industry employing debt-bonded workers resembles the 17th and 18th century institution of indentured servitude in colonial America. Migrants who could not afford to pay for their passage to the colonies from Britain or continental Europe would indenture themselves, agreeing to repay the loan with a number of years of labor at the destination. The contracts that the migrants entered into were strictly regulated and supported by the colonial governors, eager to meet labor shortages in the growing tobacco and grain sectors. Enforcement of the contracts by the authorities limited worker abuses, but also discouraged workers from violating the contracts by, for example, running away from their employer and hiding with the Indians (see Galenson (1984)).

### 3.2.1 Self-Financed Migration

Consider first the problem facing a migrant who pays for migration cost out of accumulated savings in the source country. His objective is to maximize utility of consumption over a planning horizon which is assumed to extend from time 0 to  $T$ . During the period  $[0, \phi]$  he earns the source-country wage,  $w$ , consumes  $c_t$  at each instant, and saves the rest of his income to pay for the cost of migration,  $K$ , at the optimally-chosen time of departure,  $\phi$ . From time  $\phi$  until  $T$ , he stays in the host country, earns  $w^* > w$ , consumes at the rate  $c_t^*$ , and is able to lend and borrow at the host-country risk-free interest rate  $r^*$ .

The migrant's problem is to choose the consumption rates at home and abroad,  $c_t$  and  $c_t^*$ , respectively, and the duration of the pre-departure, asset-accumulation period,  $\phi$ , given  $\delta$ ,  $w^*$ ,  $w$ ,  $r^*$ , and  $K$ , all of which are assumed constant. Migration takes place instantaneously and the migrant has no initial asset holdings. This last assumption is relaxed in Section 4.

The objective function can be written as

$$\max_{c_t, c_t^*, \phi} \int_0^\phi u(c_t) e^{-\delta t} dt + \int_\phi^T u(c_t^*) e^{-\delta t} dt. \quad (3.1)$$

In maximizing (3.1), the migrant faces two budget constraints. First, over the pre-migration period, his undiscounted savings must sum up to the cost of migration:<sup>11</sup>

$$\int_0^\phi (w - c_t) dt = K, \quad (3.2)$$

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<sup>11</sup>In the absence of more attractive alternatives, the migrant is assumed to keep his savings hidden at home until the point of departure. For very poor source countries with underdeveloped financial markets, this seems to be the most realistic assumption. Lending out the money may not be practical if there are risks of default or delay in loan repayment. Assuming, instead, that he can get some interest rate  $\rho$  on his savings prior to migration, would rotate counter-clockwise the negatively-sloped time path of his source-country consumption and enable him to migrate slightly sooner.

Second, his net savings while abroad, discounted at the foreign risk-free rate  $r^*$ , must be equal to zero in the absence of a bequest motive:

$$\int_{\phi}^T (w^* - c_t^*) e^{-r^* t} dt = 0. \quad (3.3)$$

Let us assume the utility function takes the following CRRA form,  $u(c_t) = \frac{c_t^{1-\theta}}{1-\theta}$ , where  $1/\theta$  is the elasticity of intertemporal consumption substitution (EICS). Then the consumption path during the period of asset accumulation  $[0, \phi]$  is given by (all the derivations are relegated to the Appendix)

$$c_t = c_0 e^{-\frac{\delta}{\theta} t}, \quad (3.4)$$

so that the migrant's consumption rate, while in the source country, declines at a proportional rate equal to the product of EICS and the migrant's rate of time preference. Substituting (6.11) in the budget constraint (3.2) we get

$$\phi w - \frac{\theta c_0}{\delta} (1 - e^{-\frac{\delta}{\theta} \phi}) = K, \quad (3.5)$$

which equates the migrant's savings in the source country to the cost of migration.

If we assume for simplicity, as is usually done in the related literature, that the migrant's rate of time preference,  $\delta$ , equals the risk-free rate,  $r^*$ , then the migrant's consumption abroad is constant ( $c_t^* = c^*$ ) and equal to his income,  $w^*$ . With  $c^* = w^*$  the optimality condition with respect to the departure date can be written as

$$[u(w^*) - u(c_{\phi})] e^{-\delta \phi} - c_0^{-\theta} (w - c_{\phi}) = 0, \quad (3.6)$$

where  $c_{\phi} = c_0 e^{-\frac{\delta}{\theta} \phi}$ . Thus at the optimal time of departure from the source country, the utility sacrificed by staying at home an instant longer,  $[u(w^*) - u(c_{\phi})] e^{-\delta \phi}$ , must be equal to the benefit,  $c_0^{-\theta} (w - c_{\phi})$ , which is the utility value of the savings accumulated over that unit of time. Note that on arrival in the host country, the migrant's consumption jumps instantaneously from  $c_{\phi}$  to  $w^*$ .

Eqs. (3.5) and (3.6) can be solved for the two key endogenous variables,  $c_0$  and  $\phi$ , as functions of the exogenous variables that describe the environment facing the migrant:  $w$ ,  $w^*$ , and  $K$ . The comparative statics results are provided in Appendix 3.7.1.

Of greater interest to us is the level of discounted lifetime utility,  $U^{SF}$ , enjoyed by a migrant under the self-finance arrangement:

$$U^{SF} = \frac{1}{\delta(1-\theta)} \left[ \theta c_0^{1-\theta} (1 - e^{-\frac{\delta}{\theta}\phi}) + (w^*)^{1-\theta} (e^{-\delta\phi} - e^{-\delta T}) \right], \quad (3.7)$$

where both  $c_0$  and  $\phi$  are optimally chosen. We will subsequently compare this utility with the levels enjoyed under alternative arrangements to determine which of the available options is superior.

### 3.2.2 Debt-Bonded Migration

Instead of saving at home, a liquidity-constrained agent may choose to borrow from a smuggling organization in order to pay for the cost of migration. In that case he gets smuggled into the destination country at time 0, where he stays until  $T$ , but commits to repay the entire debt by the time  $\tau \in (0, T)$ . The interest rate on the debt,  $r$ , is assumed to be greater than the foreign risk-free rate,  $r^*$ . During the period  $[0, \tau]$  he works for (a partner of) the smuggling organization at the bonded wage,  $w^b$ . We assume that  $w < w^b < w^*$  which, in reality, corresponds to most cases of debt-bonded migration. Once the debt is repaid, the migrant is released from bondage and is free to earn  $w^*$ , as well as to lend and borrow at the rate  $r^*$ . As it is rarely the case that a migrant is able to default on a loan from the smuggling organization, we assume that the loan is always paid back.<sup>12</sup>

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<sup>12</sup>Numerous media reports seem to suggest that debt-bonded migrants, especially in the sex industry, are coerced, subjected to violence and sometimes even indefinite slavery. An extensive, 132 page report by Human Rights Watch (2000) on the experience of debt-bonded Thai sex workers in Japan, provides strong indications that cases of abuse are

The migrant's objective is to maximize his lifetime utility

$$\int_0^\tau u(c_t^b) e^{-\delta t} dt + \int_\tau^T u(c_t^{b*}) e^{-\delta t} dt, \quad (3.8)$$

with respect to the duration of the debt-repayment period,  $\tau$ , his consumption rates while indebted,  $c_t^b$ , and after being released from bondage,  $c_t^{b*}$ , subject to two budget constraints: First, during the bondage period, the present value of his savings, discounted at the smuggler's rate of interest,  $r$ , must be equal to the size of the debt:

$$\int_0^\tau (w^b - c_t^b) e^{-rt} dt = K \quad (3.9)$$

Second, once the debt is repaid, the migrant's savings over the remainder of his planning horizon, discounted at the risk-free rate, must sum up to zero:

$$\int_\tau^T (w^* - c_t^{b*}) e^{-r^*t} dt = 0. \quad (3.10)$$

Following the standard optimization techniques, we derive the migrant's optimal consumption path during the period of indebtedness as

$$c_t^b = c_0^b e^{\frac{r-\delta}{\theta}t}, \quad (3.11)$$

so that the consumption rate while in bondage grows at a proportional rate equal to the product of the EICS and the difference between the rate of interest charged by the smuggler and the migrant's rate of time preference.

Combining (3.11) with (3.9) we obtain

$$\frac{w^b}{r} (1 - e^{-r\tau}) - \frac{c_0^b}{g} (e^{g\tau} - 1) = K, \quad (3.12)$$

where  $g \equiv \frac{r-\delta}{\theta} - r$  is the proportional growth rate of the discounted (time 0) value of the consumption rate  $c_t^b$ .

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an exception rather than the rule. The vast majority of migrants are fully aware of the conditions of employment abroad before entering into their contracts, which in turn (at least in the case of Japan) are largely respected by the employers. It is also important to note that debt-bonded migrants are employed in a wide range of industries throughout the world and do not only consist of sex workers.

Having assumed that  $\delta = r^*$ , the consumption rate abroad of a debt-free migrant (i.e., after time  $\tau$ ), is constant at  $c^{b*} = w^*$ . Then the optimality condition with respect to the debt-repayment date can be written as

$$[u(w^*) - u(c_\tau^b)]e^{-r^*\tau} - (c_0^b)^{-\theta}(w^b - c_\tau^b)e^{-r\tau} = 0, \quad (3.13)$$

which states that when  $\tau$  is optimally chosen, the cost (in terms of utility) of remaining in bondage an instant longer,  $[u(w^*) - u(c_\tau^b)]e^{-r^*\tau}$ , must be equal to the benefit,  $(c_0^b)^{-\theta}(w^b - c_\tau^b)e^{-r\tau}$ , which is the utility value of net savings accumulated during this extra instant. Noting that  $c_\tau^b = c_0^b e^{\frac{r-\delta}{\theta}\tau}$ , eqs. (3.12) and (3.13) can be solved for the optimal length of the repayment period,  $\tau$ , and the initial consumption rate,  $c_0^b$ , as functions of the exogenous variables (see Appendix 3.7.2 for comparative statics results and Djajić and Vinogradova (2012) for a more detailed analysis a debt-bonded migrant's behavior). At the time of release from bondage the migrant's consumption jumps instantaneously from  $c_\tau^b$  to  $w^*$ .

The discounted lifetime utility of a debt-bonded migrant is given by

$$U^{DB} = \frac{(c_0^b)^{1-\theta}}{1-\theta} \left[ \frac{e^{g\tau} - 1}{g} \right] + \frac{(w^*)^{1-\theta}}{1-\theta} \left[ \frac{e^{-\delta\tau} - e^{-\delta T}}{\delta} \right], \quad (3.14)$$

when  $c_0^b$  and  $\tau$  are optimally chosen.

### 3.2.3 No Migration

Another option available to a potential migrant is simply to remain permanently in the source country and work for the wage  $w$ . On the assumption that he faces a constant rate of interest,  $\rho$ , equal to his rate of time preference,  $\delta$ , the time path of his consumption is flat with  $c_t = w$ .<sup>13</sup> The discounted

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<sup>13</sup> Assuming that  $\rho \neq \delta$  would affect the time profile of the agent's consumption but would not alter the principal findings of this paper. Note the distinction we make between the opportunities in the credit market facing a non-migrant and a worker intending to migrate. We assume that the latter cannot borrow in the local market at the interest rate



lifetime utility stemming from his optimal consumption program is then given by

$$U^{NM} = \frac{w^{1-\theta}}{1-\theta} \left[ \frac{1 - e^{-\delta T}}{\delta} \right], \quad (3.15)$$

where NM stands for "no migration".

In the next section we compare the three options by means of numerical simulations. Our aim is to (i) identify the conditions under which international migration is optimal and, (ii) when migration does increase lifetime welfare, under what conditions do migrants prefer debt-bondage over self-finance as a way of meeting migration costs.

### 3.3 Comparing the Alternatives

The choices available to a potential migrant are: (a) no migration (NM), resulting in utility  $U^{NM}$ , (b) self-financed migration (SF), resulting in utility  $U^{SF}$ , and (c) debt-bonded migration (DB), giving rise to a utility level  $U^{DB}$ . The relationship among these options is illustrated in figure 3.1, where we have the ratio of the host- to home-country wage on the vertical axis and the ratio of the migration cost to the home-country wage on the horizontal axis. The  $SF = NM$  locus shows combinations of  $w^*/w$  and  $K/w$  such that a potential migrant is indifferent between self-financed migration and no migration.<sup>14</sup> The schedule is drawn for  $T = 30$  years,  $\theta = 0.95$ ,  $\delta = \rho = r^* = \underline{\rho}$  because enforcement of a loan agreement with the borrower abroad is more costly for the local money lenders. See Taylor (2006). Note, in addition, that a non-migrant without any access to financial markets is constrained to consume his current income ( $c_t = w$ ).

<sup>14</sup>Migration costs in our model are represented by  $K$ , the monetary cost of moving to the host country. In reality, migration costs involve much more than simply paying for a move. There are also the non-pecuniary cost of separation from family and friends, the cost of depreciating social capital, etc. (see Schiff, 2006). These non-pecuniary costs are

5% per annum, while wages  $w^*$  and  $w$  are measured as flows per week, with  $w$  normalized to 1. These same values are used in our calculations throughout the paper.<sup>15</sup> Anywhere above and to the left of the  $SF = NM$  schedule,  $U^{SF} > U^{NM}$ , so that a worker is better off migrating under the self-finance arrangement rather than staying permanently at home. In the region below and to the right of  $SF = NM$  it does not pay to migrate if migration has to be self-financed.

The  $SF = DB$  locus shows combinations of  $w^*$  and  $K$  such that a potential migrant is indifferent between self-financed migration and debt-bonded migration under the assumptions that the smuggling organization charges  $r = 40\%$  per annum and offers a bonded wage which is only two thirds of the market wage in the host country (i.e,  $w^b = (1 - \sigma)w^*$ , where  $\sigma = 1/3$ ). What can make bondage appealing to potential migrants, in spite of the high interest rate charged by the smuggling organization and the prospect of being underpaid abroad, is that this financing mode gets them sooner to the foreign, high-wage country. For any given  $\sigma$ , getting abroad sooner has a greater impact on welfare, the larger the international wage differential. High interest charges on loans provided by the smuggling organization are, on the other hand, a disadvantage, the weight of which is heavier, the higher the

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without a doubt large, although very little empirical evidence is available on this issue. Let  $K$  be the total migration costs, consisting of monetary ( $M$ ) and non-pecuniary costs ( $N$ ). If only  $M$  needs to be financed, we would have to replace  $K$  by  $M$  in the migrant's budget constraint and subtract the utility value of  $N$  from  $U^{SF}$  and  $U^{DB}$  in comparing the various options available to potential migrants in the figure. The value of  $N$  may depend on the mode of migration as well as the time of departure from the source country.

<sup>15</sup>We have tried a wide range of values for  $T$  and  $\theta$  in our simulations, only to find that the main results of the paper remain unaffected. With a longer time horizon,  $T$ , an increase in  $K$  can be shown to require a smaller increase in  $w^*$  to keep the utility of SF equal to that of NM, making the  $SF = NM$  schedule flatter. By contrast, an increase in the degree of concavity of utility function makes the  $SF = NM$  schedule steeper. That is, for any given increase in  $K$ , it requires a larger increase in future income (and hence  $w^*$ ) to keep the agent indifferent between SF and NM. Similar analysis can be conducted for the other two schedules in figure 3.1.

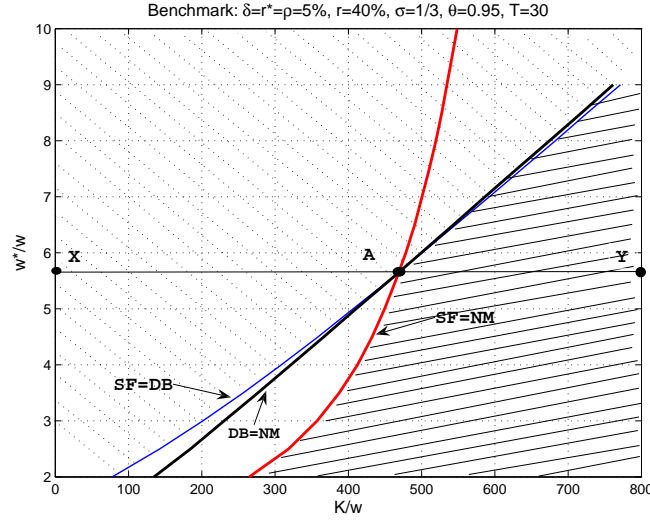


Figure 3.1: Optimal arrangements for financing migration costs.

cost of migration. For a given  $r$  and  $\sigma$ , this implies a positive relationship between the foreign wage and the cost of migration that makes potential migrants indifferent between self financing their migration costs and borrowing from a smuggling organization. For any combination of the foreign wage and migration cost that is above or to the left of the  $SF = DB$  locus, DB is preferred over SF.

Finally, agents are indifferent between debt-bonded migration and "no migration" along the  $DB = NM$  schedule. Above it,  $U^{DB} > U^{NM}$ , while below it, debt-bonded migration is less attractive than the NM option. The three schedules intersect at point A and serve to identify the combinations of  $w^*$  and  $K$  for which each of the three options is optimal.<sup>16</sup> Source-country workers will opt for debt-bonded migration when combinations of  $w^*$  and  $K$  fall into the dotted area above the  $SF = DB$  schedule to the left of point A and above the  $DB = NM$  schedule to the right of A. Self-finance is optimal when combinations of  $w^*$  and  $K$  fall into the white, unshaded area between

<sup>16</sup>All three schedules must always intersect at the same point. Consider a point of intersection between  $SF = DB$  locus and the  $SF = NM$  locus. For that combination of  $w^*$  and  $K$  it must also be the case that  $DB = NM$ .

the  $SF = DB$  and the  $SF = NM$  schedules below and to the left of point A. No migration is optimal in the remaining area shaded by thin lines.

The figure illustrates some obvious points, but it also reveals a number of interesting implications of our analysis. First, it shows that NM is optimal when migration costs are high, while the foreign wage is not attractive enough to warrant moving abroad. By contrast, when migration costs are low and the foreign wage is high, debt-bonded migration is optimal. The low  $K$  and high  $w^*$  ensure, respectively, that the debt burden is not too heavy and that the loan can be repaid relatively quickly out of earnings abroad, even at an exorbitant rate of interest charged by the smuggler. For somewhat higher migration costs and/or lower foreign wage, the self-finance option dominates debt-bondage in the unshaded region to the left of point A. This is because a higher  $K$  imposes a larger debt that must be serviced under DB at a high rate of interest, while a reduction in  $w^*$  relative to  $w$  erodes the only advantage of becoming a bonded laborer. Self-finance is then the optimal way to pay for migration costs.

An important implication of this analysis is that, by increasing  $K$ , tougher border controls help reduce the incidence of debt-bondage.<sup>17</sup> This goes against the conventional wisdom that higher migration costs fuel growth of debt-bondage. The conventional view is based on the notion that if a potential migrant's wealth is smaller than migration cost, he will be inclined to borrow from the smuggler. Once we allow for saving for the purpose of meeting migration costs, we find that an increase in  $K$  makes DB *less* attractive relative to SF, but also relative to NM.

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<sup>17</sup>Although the precise relationship between the intensity of border controls and the value of  $K$  depends on the technology of enforcement, the characteristics of the market for human smuggling, and numerous other factors, we are interested here in only the qualitative impact of a policy change on the value of  $K$ . There is in fact very little evidence on the quantitative effect of a change in the intensity of border patrols and  $K$ , other than in the case of the Mexico-US border. See, e.g., Gathmann (2008) and Hanson and Spilimbergo (1999).

An increase in border controls, however, has different implications depending on the magnitude of the international wage differential. For relatively low values of  $w^*/w$  (i.e., below the line XAY in figure 3.1), a marginal increase in  $K$  that is effective in reducing debt-bonded migration will result in an offsetting increase in self-financed migration. In that range of values of  $w^*/w$ , a higher  $K$  induces migrants to switch from debt bondage to self finance, but does not discourage them from attempting to migrate. It is only for values of  $w^*/w$  above the intersection of the three schedules that tougher border enforcement measures that deter debt-bonded migration are also effective in reducing illegal immigration one for one. In that range of values of  $w^*/w$  and  $K$ , it does not pay to switch to SF, but rather to NM.

Apart from enforcement measures at the border, host countries have in place various internal controls, including worksite inspections and employer sanctions that make it more costly for firms to hire undocumented workers. These measures undoubtedly affect the wage paid to debt-bonded migrants and the interest rate charged on their debt. The effects of an increase in  $r$  from 40% to 60%, are illustrated in figure 3.2. The dashed schedules correspond

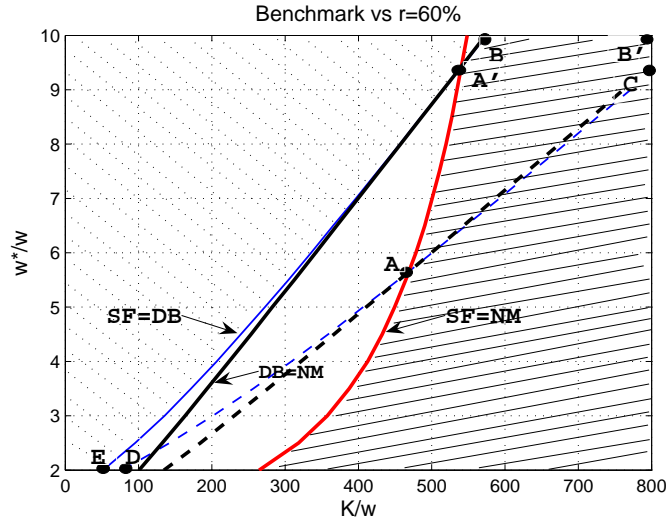


Figure 3.2: Effect of an increase in  $r$ .

to the benchmark case, while the solid ones are drawn for  $r = 0.6$ . Note

that the  $SF = NM$  schedule is unaffected since an increase in  $r$  has no influence on the attractiveness of SF in relation to NM. It does, however, make debt-bonded migration less appealing: The dotted area is now smaller, while the "self-finance", unshaded area is larger by the amount EA'AD. The "no-migration" area also expands at the expense of DB to include the area A'BB'CA. For combinations of  $w^*$  and  $K$  within this area, it no longer pays to migrate if the rate of interest charged by a smuggler is raised from 0.4 to 0.6 per annum.

The implications of an increase in  $\sigma$ , the proportion by which the bonded wage falls short of the foreign free-market wage, are very similar to those of an increase in  $r$ : The  $SF = DB$  and  $DB = NM$  schedules shift up and to the left to intersect the unaffected  $SF = NM$  locus at higher levels of both  $w^*/w$  and  $K/w$ . The area of "debt-bondage" is thus reduced while the areas of "self-finance" and "no migration" expand in a manner very similar to that illustrated in figure 3.2. These findings suggest that tougher enforcement measures which increase the risks facing smugglers and employers of bonded migrants, thereby contributing to an increase in  $r$  and/or  $\sigma$ , are likely to *reduce* the incidence of debt-bonded migration, *increase* the incidence of self-financed migration and *reduce* the overall migration flow.<sup>18</sup> The reduction in

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<sup>18</sup>By tougher enforcement, we mean harsher penalties for smugglers and employers of bonded labor, while continuing to assume that the probability of an illegal alien getting deported or otherwise punished by the authorities is zero. Here we follow the seminal work of Ethier (1986) in assuming that the internal enforcement measures are directed strictly at the employers (in our case, employers of bonded labor) rather than those who work for them. If we take the example of the U.S.A., worksite inspections and apprehensions of undocumented workers over the last two decades did not typically result in deportations. Workers without proper documentation were simply summoned to appear in front of a judge at a subsequent date. The vast majority of them did not show up at the hearing (see Martin and Miller (2000)). For an analysis of how the prospect of deportation affects the behavior of debt-bonded migrants, see Djajić and Vinogradova (2012) and for the case of debt-free illegal aliens in the context of a dynamic stochastic optimization model see Vinogradova (2010, 2011).

the flow will be from the source countries whose emigrants face an environment characterized by very large values of  $w^*/w$  and  $K/w$ , as shown by the area A'BB'CA in figure 3.2. The switch from debt bondage to self finance, with no reduction in the flow, will be from the economies with intermediate values of  $w^*/w$  and  $K/w$  as in the area EA'AD.

### 3.4 Role of Family Support

Consider next the possibility of a migrant being able to cover a fraction  $\alpha$  of  $K$  by borrowing from a network of family or friends. This obviously facilitates migration and increases the utility of a migrant, regardless of whether the balance of migration costs,  $(1 - \alpha)K$ , is self-financed or funded by entering into a debt-bondage agreement. In the case of self-finance, partial support from the family enables the migrant to pay for migration costs sooner and start earning the high foreign wage earlier in life. In the case of debt bondage, family support serves to substitute low-interest debt, owed to the family, for high-interest debt owed to the smuggler. In addition, a family loan helps the migrant get out of bondage sooner and enables him to repay the amount owed to the family while earning  $w^*$ , rather than the lower, bonded wage  $w^b$ .

The financing role of a family network is of paramount importance when it comes to long-haul routes, characterized by high values of  $K/w$  and  $w^*/w$ , such as in the case of Chinese migration to the West. The history of that migration stream is one of early migrants providing newcomers with partial (and in many cases total) financing of their migration costs. Once the latter pay off their debts to smugglers and/or relatives and neighbors, they strive to develop their own entrepreneurial activities that enable them, in turn, to extend financial support to others: their siblings, other relatives, and the next generation of immigrants (see Kwong (1997) and Gao (2004)).

### 3.4.1 Self-Finance with Family Support

We begin with the case of self-finance under the assumption that the rate of interest at which the migrant is obliged to service the family loan is equal to the risk-free rate  $r^*$ . The migrant's objective function remains identical to (3.1) but the two budget constraints are modified as follows: A self-financed migrant has to save  $(1 - \alpha)K$  out of the source-country wage until the optimally chosen time of migration,  $\tilde{\phi}$ , and repay  $\alpha K$  to his family while working abroad from time  $\tilde{\phi}$  to  $T$ .

$$\int_0^{\tilde{\phi}} (w - \tilde{c}_t) dt = (1 - \alpha)K, \quad (3.16)$$

$$\int_{\tilde{\phi}}^T (w^* - \tilde{c}_t^*) e^{-r^*(t-\tilde{\phi})} dt = \alpha K. \quad (3.17)$$

A tilde over a variable indicates that it pertains to the case of family support. The level of discounted lifetime utility enjoyed by a migrant is then given by:

$$\tilde{U}^{SF} = \frac{1}{1 - \theta} \left[ \frac{\theta \tilde{c}_0^{1-\theta}}{\delta} (1 - e^{-\frac{\delta}{\theta} \tilde{\phi}}) + \frac{(\tilde{c}^*)^{1-\theta}}{\delta} (e^{-\delta \tilde{\phi}} - e^{-\delta T}) \right], \quad (3.18)$$

where  $\tilde{c}_0$ ,  $\tilde{c}^*$  and  $\tilde{\phi}$  are the solutions to the following system of equations:

$$\tilde{\phi} w - \frac{\theta \tilde{c}_0}{\delta} (1 - e^{-\frac{\delta}{\theta} \tilde{\phi}}) = (1 - \alpha)K, \quad (3.19)$$

$$\frac{w^* - \tilde{c}^*}{r^*} (1 - e^{r^*(\tilde{\phi}-T)}) = \alpha K, \quad (3.20)$$

$$[u(\tilde{c}_{\tilde{\phi}}) - u(\tilde{c}^*)] e^{-\delta \tilde{\phi}} + \tilde{c}_0^{-\theta} (w - \tilde{c}_{\tilde{\phi}}) - (\tilde{c}^*)^{-\theta} (w^* - \tilde{c}^* - \alpha r^* K) e^{-r^* \tilde{\phi}} = 0$$

with derivation provided in Appendix 3.7.3.

### 3.4.2 Debt-Bonded Migration with Family Support

Consider next the problem facing a migrant who goes into debt-bondage at time 0 and covers a fraction  $\alpha$  of his migration cost by means of a family loan



agreement. He maximizes lifetime utility, which is identical to (3.8), subject to the following constraints

$$\int_0^{\tilde{\tau}} (w^b - \tilde{c}_t^b) e^{-rt} dt = (1 - \alpha)K, \quad (3.22)$$

$$\int_{\tilde{\tau}}^T (w^* - \tilde{c}_t^{b*}) e^{-r^*t} dt = \alpha K. \quad (3.23)$$

As this problem is otherwise the same as the one described in subsection 2.2, we proceed directly to the solution. The key endogenous variables,  $\tilde{c}_0^b$ ,  $\tilde{c}^{b*}$ , and  $\tilde{\tau}$ , are obtained by solving the system

$$\frac{w^b}{r} (1 - e^{-r\tilde{\tau}}) - \frac{\tilde{c}_0^b}{g} (e^{g\tilde{\tau}} - 1) = (1 - \alpha)K, \quad (3.24)$$

$$\frac{w^* - \tilde{c}^{b*}}{r^*} (e^{-r^*\tilde{\tau}} - e^{-r^*T}) = \alpha K, \quad (3.25)$$

$$[u(\tilde{c}_{\tilde{\tau}}^b) - u(\tilde{c}^{b*})] e^{-\delta\tilde{\tau}} + (\tilde{c}_0^b)^{-\theta} (w^b - \tilde{c}_{\tilde{\tau}}^b) e^{-r\tilde{\tau}} - (\tilde{c}^{b*})^{-\theta} (w^* - \tilde{c}^{b*}) e^{-r^*\tilde{\tau}} = 0, \quad (3.26)$$

where  $\tilde{c}_{\tilde{\tau}}^b = \tilde{c}_0^b e^{\frac{r-\delta}{\theta}\tilde{\tau}}$  and  $r^* = \delta < r$ .

The discounted lifetime utility in this case is given by

$$\tilde{U}^{DB} = \frac{1}{1 - \theta} \left[ \frac{(\tilde{c}_0^b)^{1-\theta}}{g} (e^{g\tilde{\tau}} - 1) + \frac{(\tilde{c}^{b*})^{1-\theta}}{\delta} (e^{-\delta\tilde{\tau}} - e^{-\delta T}) \right].$$

In the next subsection, we compare the levels of utility enjoyed under SF, DB and NM when  $\alpha \in (0, 1)$ .

### 3.4.3 Optimal Choice with Family Support

The effects of financial support from the family on the relative attractiveness of SF, DB, and NM are illustrated in figure 3.3. The dashed lines correspond to the benchmark case (no family support), while the solid lines pertain to a situation in which a family loan covers 20% of migration costs (i.e.  $\alpha = 0.2$ ). Note that family support makes debt-bonded migration more attractive in relation to *both* SF and NM, expanding the DB area in figure 3.3 by EABCA'F. The SF area, represented by EAG in the absence of family support, becomes

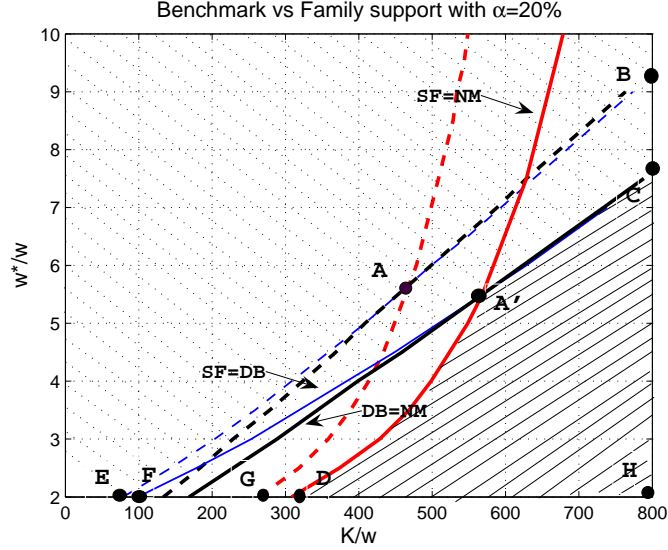


Figure 3.3: Family support with  $\alpha = 20\%$ .

FA'D. The NM area, which was the region GABH in the absence of family support, shrinks to DA'CH.

The figure illustrates three important points. First, as shown by the magnitude of the shifts of the three schedules, even a small amount of financial support from the family (20% of  $K$ ) has a substantial impact on the optimal choice with respect to SF, DB, and NM. Second, as the NM area shrinks, access to credit on reasonable terms is seen to increase the flow of migrants to the advanced countries. This is likely to take the form of self-financed (debt-bonded) migration from the relatively better off (poorer) sending countries, characterized by  $w^*/w$  that lies below (above) the XAY line in figure 3.1. This implication of our model is likely to play a key role in explaining (a) why Chinese migration to the West has consisted primarily of flows from those communities that already have family network ties abroad, while potential migrants from other mainland communities that lack such ties (and hence access to financial support) have been obliged to choose the NM option,<sup>19</sup> and (b) why the majority of Chinese immigrants that arrive in Western

<sup>19</sup>It is interesting to note that roughly 90% of Chinese immigrants living in Florence were born in the Wenzhou region of Zhejiang (see Gao (2004)). Table 7 of Gao and Poisson

Europe and North America are heavily indebted to smugglers and/or family members.<sup>20</sup>

The third point illustrated by figure 3.3 is that debt-bondage becomes the preferred financing option over self-finance for a wider range of combinations of  $w^*$  and  $K$ . This result stems from the fact that if an individual is initially indifferent between SF and DB, a family loan raises the utility of DB by more than that of SF. To confirm this, note that for a self-financed migrant, the welfare impact of a loan amounting to one unit of the numeraire obtained at time  $\phi$  (the moment of departure), is simply  $\Delta U^{SF} = u'(c_{\phi-}) - u'(c_{\phi+}^*)$ . This is the difference between his marginal utility of consumption the moment just before and just after migration under the SF arrangement. As optimal consumption *jumps to a higher level* with migration at time  $\phi$ ,  $u'(c_{\phi-}) > u'(c_{\phi+}^*)$  and so  $\Delta U^{SF} > 0$ . Similarly, a family loan in the same amount changes the welfare of a DB migrant by  $\Delta U^{DB} = u'(c_0^b) - u'(c_{\tau+}^{b*})$ . This is clearly positive because his consumption at the beginning of debt-bondage,  $c_0^b$ , is lower than that after release from bondage,  $c_{\tau+}^{b*}$ , guaranteeing that  $u'(c_0^b) > u'(c_{\tau+}^{b*})$ . To compare  $\Delta U^{SF}$  with  $\Delta U^{DB}$ , recall that in the case of no family support, a migrant's consumption abroad under SF is identical to that of a DB migrant after release from bondage. Both consume at the rate  $w^*$  when  $\delta = r^*$ . Thus, to determine the magnitude of  $\Delta U^{SF}$  relative to  $\Delta U^{DB}$  along the  $SF = DB$  schedule, we simply need to compare the value of  $c_{\phi-}$

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(2005, p. 29) shows a similar pattern: Of the 15'232 Chinese immigrants registered in 2002 by ASLC, a French organization providing Chinese migrants with a range of services, including assistance in legalizing their status, 62 percent came from Zhejiang. In contrast with potential migrants from other Chinese provinces, the ones from Zhejiang already had family network ties in France, likely providing access to financial support.

<sup>20</sup>According to Gao and Poisson (2005, p. 49), the vast majority of Chinese immigrants arriving in France in the late 1990s were indebted. Most of the migrants were from Zhejiang and practically all of them (479 out of 500 respondents) were indebted on arrival. For a majority of these migrants, the debts were in the range between 14 000 and 20 000 euros. Unfortunately, the data set used by Gao and Poisson (2005) does not identify the source of credit (i.e., human smugglers, family members or friends).

with that of  $c_0^b$ . Our calculations show that all along the  $SF = DB$  locus, an SF migrant consumes more just before migration than a DB migrant does at the beginning of debt-bondage. This implies that  $u'(c_{\phi-}) < u'(c_0^b)$  and so  $\Delta U^{DB} > \Delta U^{SF}$ . We have performed these same calculations for the effects of an increase in family support for all values of  $\alpha$  in the range  $[0, 1)$  and found that additional financing from the family *always* makes debt-bondage more attractive relative to self-finance, shifting the  $SF = DB$  schedule down and to the right.

### 3.4.4 The Role of Initial Wealth

We assumed to this point that an agent's initial holdings of assets,  $A$ , are equal to zero. If we introduce  $A$  into his budget constraint for each of the three options, we find that an additional unit of wealth has the following impact: 1) In the case of DB, it increases utility by  $u'(c_0^b)$ , 2) for a self-financed migrant, it increases utility by  $u'(c_0)$ , and 3) for an agent who remains permanently in the source country, it raises utility by  $u'(w)$ . We know from the discussion in the previous sections that  $w > c_0 > c_0^b$ , which implies that if an agent is indifferent between SF and DB or NM and DB, an extra unit of wealth raises  $U^{DB}$  relative to  $U^{SF}$  and  $U^{NM}$ , causing the  $SF = DB$  and  $DB = NM$  schedules to shift down and to the right. Similarly, because an extra unit of wealth increases the utility of SF relative to that of NM, it causes the  $SF = NM$  schedule to shift down and to the right. The implications of an increase in the initial asset holdings are therefore very similar to those of an increase in the amount of financial support from the family, depicted in figure 3.3.

### 3.5 The Model and Some Stylized Facts

After a thorough search for empirical evidence that could possibly be used to test the predictions of our model at both the micro and macro levels, we have found two samples that provide information as to whether a migrant who borrowed money to pay for migration costs is debt bonded to a smuggling organization or indebted to family members or a financial institution after putting up collateral. One of these samples, described in Jones and Pardthaisong (1999), covers 22 individuals with complete information provided for only 11 *temporary* migrants, 3 of whom were debt-bonded. The key factors that distinguish the three DB migrants from the eight SF respondents is their occupation and wage abroad. All three were employed in the sex industry in Japan and, as indicated in Table 6 of Jones and Pardthaisong (1999), earned a multiple (5 - 10) of the wages received by SF migrants in the various destination countries. In terms of our model,  $w^*/w$  is much larger for the three, so that in spite of having been charged a considerably higher  $K$  than the rest of the sample, it still paid for them to choose DB over SF as the best financing option.

Another data set based on interviews with return migrants in Thailand in the late 1990's, gathered for the Sobieszczyk (2000) study, is considerably richer in terms of information about personal characteristics of the respondents, although it lacks evidence on their pre-migration wage.<sup>21</sup> The data set contains observations on 104 migrants (including 13 former debt-bonded) and provides information on marital status, number of children, age at migration, level of education, commission paid to go abroad, salary abroad, destination country, and other variables. The thirteen former debt-bonded migrants worked in Japan (6), Singapore (5), Macao (1), and Taiwan (1). The other 91 migrants, reported to be self-financed, worked in Taiwan (44), Japan (29),

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<sup>21</sup>Only data on *household* income is provided. Households vary in size from 1 to 7 with no indication of the number of income earners within a household, making it difficult to extract the value of  $w$  pertaining to the migrating member.

Hong Kong (6), Brunei (4), South Korea (4), Malaysia (2), and Singapore (2).

On the basis of this data set, which admittedly does not allow for rigorous empirical analysis, we are nonetheless able to draw some insights on the relationship between personal characteristics of migrants and their choice between DB and SF. We find that higher age at the time of migration is associated with a lower probability of choosing DB over SF. This is consistent with the fact that a DB migrant can leave the source country earlier than an SF migrant who must first save at home to pay for migration expenses. Overall, the analysis of the data set indicates that DB migrants tend to be relatively young, to have a low level of education, and to migrate to high-income/high-wage countries. Of the thirteen DB migrants in the sample, the majority worked in Japan and Singapore, the two highest-income destinations. By contrast, more than half of the SF migrants worked in Taiwan and Malaysia, the two poorest of the seven destinations. This evidence is consistent with the prediction of our model that the higher the international wage differential, the stronger the incentive to choose DB over SF as the optimal financing option.

With respect to the choice of destination for DB migrants, a similar pattern has been observed centuries ago in colonial America. Many of the migrants in that era chose to meet the cost of passage from Europe by entering into servitude contracts.<sup>22</sup> In relation to the predictions of our model, it is interesting to note that the proportion of immigrants that chose servitude as a means of financing migration varies significantly across colonies. Colonies

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<sup>22</sup> The cost of ocean passage from Britain to the American colonies in the 17th and 18th centuries was roughly one half of a year's income for a low-skilled British emigrant and a year's income for someone migrating from Germany (see Grubb (1985) and Galenson (1984)). According to Smith (1947, p. 336), if one excludes Puritan migration of the 1630's, "...not less than half nor more than two thirds of all white immigrants to the colonies were indentured servants, redemptioners or convicts." For the period from 1785 to 1804, Grubb (1985, p.319) estimates that the incidence of indentured servitude among the 7837 German immigrants arriving in Philadelphia was 44.8% overall and over 50% for single adults.

with a relatively high proportion of servants among their immigrants were Virginia, Maryland and Pennsylvania. The Carolinas and Georgia to the south and the colonies to the north of Pennsylvania had a much lower incidence of servitude.<sup>23</sup>

Why were some colonies so attractive to debt-bonded migrants while others received mostly self-financed immigrants? Our model predicts that for any given cost of migration (and the cost of passage from England was roughly the same at this time, regardless of which colony was chosen as the destination), a higher ratio of host- to source-country wage makes debt-bonded migration more attractive relative to self-finance. The colonies that show high incidence of servitude among their immigrants were precisely those that offered better compensation and working conditions. According to Grubb (1985), the productivity of farm labor in the northern colonies was not high enough to enable recruiters to offer competitive contracts (i.e., short enough duration of time that the migrant had to serve in order to cover the cost of transport). The highest productivity of labor in agriculture was in the middle colonies, where tobacco and grains were produced for export. Availability of relatively cheap land in that region also meant that a servant could expect a decent income from eventually farming his own land after release from bondage. Colonies north of Pennsylvania lacked the lucrative export crops that the middle and southern colonies produced. The southern colonies, however, were unattractive for those entering servitude contracts because the working conditions in the rice fields of South Carolina were perceived to be much less favorable than those on tobacco and grain farms of the middle colonies (see Grubb (1985, p.335)).

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<sup>23</sup> Between 1773 and 1776, emigration records were kept by English authorities, including the name of the colony of destination and whether the passenger paid the fare in full or entered, instead, into a servitude contract. As reported in Table 6 of Grubb (1985, p.334), the percentages of English emigrants destined for various colonies as servants are as follows: Maryland, 98.33%; Virginia, 90.35% ; Pennsylvania, 78.81%; Carolinas, 23.58%; Georgia, 17.86%; New York, 11.55%; Canada, 9.68%; Nova Scotia, 7.76%; and New England, 1.85%.

Later in the 19th century, debt-bonded migration from India and China met shortages of labor on sugar plantations of the West Indies and Hawaii, in the mines of California and South America, and on the building of railroads. These were the types of employment avoided by the free white settlers. Coincidental with the bound Asian migration was the primarily self-financed migration of Europeans to the United States. Galenson (1984, p.25) explains this phenomenon in a way consistent with the predictions of our model, by pointing to migration costs. For Asian migrants to the Western Hemisphere, they were 20 to 40 times higher, when measured in terms of per capita income of the source country, than they were for migrants from Great Britain, Ireland, Germany, and the Scandinavian countries. Self-finance was then an attractive option for the Europeans, whose migration costs were to the left of point A in Figure 1, while for Indian and Chinese migrants, facing  $K/w$  to the right of point A, DB was the way to go. This holds true regardless of whether migration flows were triggered at the time by an increase in the destination wage or a reduction in transport costs.

Given the scarcity of evidence on modern-day debt-bonded migration, a thorough empirical analysis of the predictions of our model will have to be postponed to a future date. Should data become available, there are many fruitful directions in which empirical work could be conducted. One would ideally like to have data on migration costs, potential earnings abroad (both in bondage and after release) and at home for each worker, liquid asset holdings, and data on the availability and cost of credit. The optimal choice predicted by the model can then be confronted with the data on the actual choices made by individual agents.

As the conditions facing potential migrants differ across countries of emigration, but also within a given country, depending on the occupational status and other personal characteristics of agents, one would expect that the optimal choice varies both across individuals and countries. Nonetheless, for any given distribution of skills and other individual characteristics, we would expect that if migration costs are high enough to make NM the preferred op-



tion, an exogenous reduction in  $K$  would tend to increase SF migration from countries where  $w^*/w$  is relatively low and increase DB migration from other source countries where  $w^*/w$  is relatively high. Similarly, an increase in the demand for labor in a host country (a rise in  $w^*$ ) should have a differential impact on the mode of migration from various countries, depending on the level of  $K/w$ . If NM is the preferred option in the initial equilibrium, an increase in  $w^*$  can be expected to increase the incidence of DB (SF) from source countries with a relatively high (low)  $K/w$ .

### 3.6 Conclusion

Liquidity constraints impede many potential migrants from realizing their migration plans. The main objective of the present study is to characterize the economic environment in which international migration is an attractive option for such individuals and, when it is, under what conditions they choose debt-bondage as the optimal means of financing migration costs. What makes debt-bondage appealing to potential migrants, in spite of the high interest charges and the prospect of being underpaid abroad while repaying the debt, is that this financing mode brings them sooner to the foreign, high-wage economy. Getting abroad sooner is of greater significance the larger the international wage differential. High interest charges on loans provided by human smugglers are, however, a disadvantage, the weight of which is greater, the higher the cost of migration. We therefore find that debt bondage is the preferred mode of financing when the international wage differential is large in relation to migration costs.

Another important implication of our analysis is that tougher border control measures, by increasing the cost of migration, help to reduce the incidence of debt-bonded migration. This goes against the conventional wisdom that higher costs compel more migrants to become indebted to the smugglers. Quite to the contrary, stricter border controls make debt-bonded

migration *less* attractive in relation to self-financed migration. Tougher internal enforcement measures that increase the risks and costs of operating a human-smuggling organization or employing bonded laborers tend to reduce migration flows and the incidence of bonded migration relative to self-financed migration. The reductions in the flows are shown to be from the very poor source countries, where the local wage is low in relation to the cost of migration and the host-country wage. From other source countries with sufficiently high local wages, these policies do not deter illegal immigration, but rather induce a switch from debt-bonded to self-financed migration.

The possibility of borrowing from family and friends (or financial institutions) on reasonable terms always makes migration more attractive in relation to the "no-migration" option. Under the self-finance arrangement, it enables the migrant to get abroad earlier and earn the high foreign wage over a longer period of time. In the case of bonded migration, a family loan allows the individual to get out of bondage sooner and repay the family loan while earning the free-market wage rather than the bonded wage. Interestingly, with partial financial support from the family, debt bondage becomes more attractive, not only in relation to no migration, but also with respect to self finance.

Debt-bonded migration has attracted public attention primarily because of the legitimate human-rights concerns related to the fact that migrants are tied to their employers through debt, obligation, and sometimes even coercion. Many of them accept work in the host country on highly unfavorable terms and find themselves saddled with heavy indebtedness and interest charges that appear to be clearly abusive. Our analysis shows, however, that even under such highly unfavorable conditions, becoming a debt-bonded migrant and reaching the high-wage destination country relatively sooner can be more attractive than the options of remaining permanently in the source country or migrating under the self-finance arrangement. This and other results of the present study will hopefully improve our understanding of debt-bonded international migration and contribute to the formulation of policies with a sharper focus on its negative implications.

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## 3.7 Appendix

### 3.7.1 Self-Financed Migration

#### *Derivation of the Solution*

The Lagrangian function is given by

$$L = \int_0^\phi u(c_t)e^{-\delta t}dt + \int_\phi^T u(c_t^*)e^{-\delta t}dt + \lambda \left[ \int_0^\phi (w - c_t)dt - K \right] + \mu \int_\phi^T (w^* - c_t^*)e^{-r^*t}dt,$$

where  $\lambda$  and  $\mu$  are the multipliers attached to the constraints (3.2) and (3.3), respectively.

The first-order conditions,

$$\frac{\partial L}{\partial c_t} = u'(c_t)e^{-\delta t} - \lambda = 0, \quad (3.27)$$

$$\frac{\partial L}{\partial c_t^*} = u'(c_t^*)e^{-\delta t} - \mu e^{-r^*t} = 0, \quad (3.28)$$

$$\frac{\partial L}{\partial \phi} = u(c_\phi)e^{-\delta\phi} - u(c_\phi^*)e^{-\delta\phi} + \lambda(w - c_\phi) - \mu(w^* - c_\phi^*)e^{-r^*\phi} = 0, \quad (3.29)$$

and the budget constraints (3.2) and (3.3) determine the five endogenous variables  $c_t$ ,  $c_t^*$ ,  $\phi$ ,  $\lambda$ , and  $\mu$ . Equations (3.27) - (3.28) relate the marginal utilities of consumption before and after  $\phi$  to the utility values of wealth while in the source country ( $\lambda$ ) and after migration ( $\mu$ ), respectively. Eq. (3.29) states that, at the optimal time of departure,  $\phi$ , the cost of remaining in the source country for an extra instant,  $[u(c_\phi^*) - u(c_\phi)]e^{-\delta\phi}$ , must be equal to the benefit,  $\lambda(w - c_\phi) - \mu(w^* - c_\phi^*)e^{-r^*\phi}$ , which is the utility value of the savings accumulated by staying in the source country an instant longer.

#### *Comparative Statics*

Total differentiation of eqs. (3.5)-(3.6) yields the following comparative

statics results

$$\frac{d\phi}{dK} = \frac{c_0^{-\theta}}{\Delta} \frac{\theta}{c_0} (c_\phi - w) > 0 \quad (3.30)$$

$$\frac{d\phi}{dw} = \frac{c_0^{-\theta}}{\Delta} \left[ \phi \frac{\theta}{c_0} (w - c_\phi) + \frac{\theta}{\delta} (e^{\frac{-\delta}{\theta}\phi} - 1) \right] \geq 0 \quad (3.31)$$

$$\frac{d\phi}{dw^*} = \frac{u'(w^*)}{\Delta} \frac{\theta}{\delta} (e^{\frac{-\delta}{\theta}\phi} - 1) e^{-\delta\phi} < 0 \quad (3.32)$$

$$\frac{dc_0}{dK} = \frac{c_0^{-\theta}}{\Delta} \delta (c_\phi - w) > 0 \quad (3.33)$$

$$\frac{dc_0}{dw} = \frac{c_0^{-\theta}}{\Delta} (c_\phi - w) (1 - \phi\delta) \geq 0 \quad (3.34)$$

$$\frac{dc_0}{dw^*} = \frac{u'(w^*)}{\Delta} (w - c_\phi) e^{-\delta\phi} < 0, \quad (3.35)$$

where  $\Delta = \theta c_0^{-\theta-1} (w - c_\phi) (c_0 - w) < 0$ . These results can be summarized as follows: An increase in migration costs prolongs the period of saving at home prior to emigration and increases the initial consumption rate  $c_0$ . Note, however, that the consumption rate just before departure,  $c_\phi$ , is unaffected by an increase in  $K$ , as may be verified by differentiating  $c_\phi = c_0 e^{-\frac{\delta}{\theta}\phi}$  with respect to  $K$  and substituting for  $\frac{d\phi}{dK}$  and  $\frac{dc_0}{dK}$  the expressions (3.30) and (3.33), respectively.

An increase in  $w$  has an ambiguous effect on  $\phi$  and  $c_0$ , as shown in (3.31) and (3.34). This reflects the opposing forces of the income and the substitution effects of an increase in  $w$ . By contrast, an increase in  $w^*$  makes it more urgent to emigrate earlier, encouraging the migrate to save at a higher rate ( $dc_0/dw^* < 0$  in (3.35)) and leave the source country sooner ( $d\phi/dw^* < 0$  in (3.32)).

### 3.7.2 Debt-Bonded Migration

*Derivation of the solution*

The Lagrangian function is given by

$$\begin{aligned} L^b &= \int_0^\tau u(c_t^b) e^{-\delta t} dt + \int_\tau^T u(c_t^{b*}) e^{-\delta t} dt + \\ &+ \lambda^b \left[ \int_0^\tau (w^b - c_t^b) e^{-rt} dt - K \right] + \mu^b \int_\tau^T (w^* - c_t^{b*}) e^{-r^* t} dt, \end{aligned}$$



with the first-order conditions consisting of

$$\frac{\partial L^b}{\partial c_t^b} = u'(c_t^b)e^{-\delta t} - \lambda^b e^{-rt} = 0, \quad (3.36)$$

$$\frac{\partial L^b}{\partial c_t^{b*}} = u'(c_t^{b*})e^{-\delta t} - \mu^b e^{-r^*t} = 0, \quad (3.37)$$

$$\frac{\partial L^b}{\partial \tau} = u(c_\tau^b)e^{-\delta\tau} - u(c_\tau^{b*})e^{-\delta\tau} + \lambda^b(w^b - c_\tau^b)e^{-r\tau} - \mu^b(w^* - c_\tau^{b*})e^{-r^*\tau} = 0, \quad (3.38)$$

and the budget constraints (3.9) and (3.10). These five equations determine the five endogenous variables  $c_t^b$ ,  $c_t^{b*}$ ,  $\tau$ ,  $\lambda^b$ , and  $\mu^b$ . Eqs. (3.36) - (3.37) are the usual Euler equations, while (3.38) states that when  $\tau$  is optimally chosen, the cost (in terms of utility) of remaining in bondage an instant longer,  $[u(c_\tau^{b*}) - u(c_\tau^b)]e^{-\delta\tau}$ , must be equal to the benefit,  $\lambda^b(w^b - c_\tau^b)e^{-r\tau} - \mu^b(w^* - c_\tau^{b*})e^{-r^*\tau}$ , which is the utility value of net savings accumulated during this extra instant.

#### *Comparative Statics*

We totally differentiate the system of equations (3.12) and (3.13) to obtain the following comparative statics results:

$$\frac{dc_0^b}{dw^*} = -\frac{u'(w^*)e^{-\delta\tau}(w^b - c_\tau^b)e^{-r\tau}}{\Delta^b} < 0 \quad (3.39)$$

$$\frac{dc_0^b}{dw^b} = \frac{(c_0^b)^{-\theta}(w^b - c_\tau^b)e^{-r\tau}}{\Delta^b} \left[ \frac{1 - e^{-r\tau}}{r}(r - \delta) + e^{-r\tau} \right] > 0 \quad (3.40)$$

$$\frac{dc_0^b}{dK} = -\frac{(c_0^b)^{-\theta}(w^b - c_\tau^b)e^{-r\tau}}{\Delta^b}(r - \delta) < 0 \quad (3.41)$$

$$\frac{dc_0^b}{dr} = \frac{(c_0^b)^{-\theta}(w^b - c_\tau^b)e^{-r\tau}}{\Delta^b} \left[ B_r(r - \delta) - \tau(w^b e^{-r\tau} - c_0^b e^{g\tau}) \right] < 0, \quad (3.42)$$

$$\frac{d\tau}{dw^*} = -\frac{1}{\Delta^b} \left[ \frac{e^{g\tau} - 1}{g} u'(w^*)e^{-\delta\tau} \right] < 0 \quad (3.43)$$

$$\frac{d\tau}{dw^b} = \frac{1}{\Delta^b} \left[ \frac{e^{g\tau} - 1}{g} - \frac{\theta}{c_0^b}(w^b - c_\tau^b) \frac{1 - e^{-r\tau}}{r} \right] (c_0^b)^{-\theta} e^{-r\tau} \geq 0 \quad (3.44)$$

$$\frac{d\tau}{dK} = \frac{(c_0^b)^{-\theta}(w^b - c_\tau^b)e^{-r\tau}}{\Delta^b} \frac{\theta}{c_0^b} > 0 \quad (3.45)$$

$$\frac{d\tau}{dr} = \frac{(c_0^b)^{-\theta}(w^b - c_\tau^b)e^{-r\tau}}{\Delta^b} \frac{\theta}{c_0^b} \left[ -\frac{\tau c_0^b e^{g\tau} - 1}{\theta} - B_r \right] \geq 0, \quad (3.46)$$

where  $B_r = \frac{w^b}{r}(\tau e^{-r\tau} - \frac{1-e^{-r\tau}}{r}) - \frac{c_0^b}{g} \frac{1-\theta}{\theta} (\tau e^{g\tau} - \frac{e^{g\tau}-1}{g}) < 0$  represents the effect of  $r$  on the migrant's budget while in bondage and  $\Delta^b = (c_0^b)^{-\theta} (w^b - c_\tau^b) e^{-r\tau} \left[ \frac{e^{g\tau}-1}{g} (r - \delta) + (w^b e^{-r\tau} - c_0^b e^{g\tau}) \frac{\theta}{c_0^b} \right] > 0$ .

As shown in (3.39) and (3.43), an increase in  $w^*$  makes the post-bondage period more attractive, which encourages the migrant to repay the debt and get out of bondage sooner. This requires a greater effort to save while indebted, implying that  $c_t$  is lower at each point in time prior to release.

An increase in the bonded-labor wage,  $w$ , relaxes the migrant's budget constraint, allowing for higher consumption at each instant while indebted (see (3.40)). The effect on the optimal length of the repayment period in (3.44) is ambiguous, however, reflecting the conflicting forces of the income and substitution effects.

An increase in  $K$  tightens the migrant's budget constraint, causing his time profile of consumption to shift down, while also lengthening the repayment period, as indicated by eqs. (3.41) and (3.45).

As shown in (3.46), an increase in  $r$  can have either a positive or a negative effect on  $\tau$ . On the one hand, it encourages the migrant to repay the debt more quickly (see (3.42)). At the same time it also lowers the present value of savings generated in bondage, requiring a longer repayment period. When the optimal saving rate is relatively high, either because of a large  $r$  or a large gap between  $w^*$  and  $w$ ,  $d\tau/dr > 0$ . Otherwise  $\tau$  decreases with an increase in  $r$ . For a more extensive analysis of the behavior of debt-bonded migrants, see Djajić and Vinogradova (2010)

### 3.7.3 Self-Finance with Family Support

In the case of self-finance, the objective function remains identical to (3.1) but the two budget constraints are modified as follows:

$$\int_0^{\tilde{\phi}} (w - \tilde{c}_t) dt = (1 - \alpha)K, \quad (3.47)$$

$$\int_{\tilde{\phi}}^T (w^* - \tilde{c}_t^*) e^{-r^*(t-\tilde{\phi})} dt = \alpha K, \quad (3.48)$$

The Lagrangian function is now given by

$$\begin{aligned} L = & \int_0^{\tilde{\phi}} u(\tilde{c}_t) e^{-\delta t} dt + \int_{\tilde{\phi}}^T u(\tilde{c}_t^*) e^{-\delta t} dt + \tilde{\lambda} \left[ \int_0^{\tilde{\phi}} (w - \tilde{c}_t) dt - (1 - \alpha)K \right] + \\ & + \tilde{\mu} \left[ \int_{\tilde{\phi}}^T (w^* - \tilde{c}_t^*) e^{-r^* t} dt - \alpha K e^{-r^* \tilde{\phi}} \right] \end{aligned}$$

with the first-order conditions being:

$$\frac{\partial L}{\partial \tilde{c}_t} = u'(\tilde{c}_t) e^{-\delta t} - \tilde{\lambda} = 0, \quad (3.49)$$

$$\frac{\partial L}{\partial \tilde{c}_t^*} = u'(\tilde{c}_t^*) e^{-\delta t} - \tilde{\mu} e^{-r^* t} = 0, \quad (3.50)$$

$$\frac{\partial L}{\partial \tilde{\phi}} = u(\tilde{c}_{\tilde{\phi}}) e^{-\delta \tilde{\phi}} - u(\tilde{c}_{\tilde{\phi}}^*) e^{-\delta \tilde{\phi}} + \tilde{\lambda} (w - \tilde{c}_{\tilde{\phi}}) - \tilde{\mu} (w^* - \tilde{c}_{\tilde{\phi}}^* + \alpha r^* K) e^{-r^* \tilde{\phi}} = 0, \quad (3.51)$$

and the budget constraints (3.47) and (3.48). These five equations determine the five endogenous variables  $\tilde{c}_t$ ,  $\tilde{c}_t^*$ ,  $\tilde{\phi}$ ,  $\tilde{\lambda}$ , and  $\tilde{\mu}$ . From (3.49), the consumption path during the period of asset accumulation  $[0, \tilde{\phi}]$  is given by

$$\tilde{c}_t = \tilde{c}_0 e^{-\frac{\delta}{\theta} t}, \quad \tilde{c}_0 = \tilde{\lambda}^{-1/\theta}. \quad (3.52)$$

As in our earlier analysis of self-financed migration, the migrant's consumption rate, while still in the source country, declines at a proportional rate equal to  $\delta/\theta$ . Substituting eq. (3.52) into the budget constraint (3.47), we obtain

$$\tilde{\phi} w - \frac{\theta \tilde{c}_0}{\delta} (1 - e^{-\frac{\delta}{\theta} \tilde{\phi}}) = (1 - \alpha)K, \quad (3.53)$$

showing that the migrant must save in the source country just enough to pay for a fraction  $(1 - \alpha)$  of migration costs which are not covered by a family loan agreement.

Assuming once again that  $r^* = \delta$ , (3.50) implies that the migrant's time profile of consumption is flat at the rate  $\tilde{c}_t^* = \tilde{c}^* = \tilde{\mu}^{-1/\theta}$ . Combining this with the budget constraint (3.48) we obtain:

$$\frac{w^* - \tilde{c}^*}{r^*} (1 - e^{r^*(\tilde{\phi}-T)}) = \alpha K, \quad (3.54)$$

so that the family loan in the amount  $\alpha K$  is repaid (with interest,  $r^*$ ) out of income earned in the host country.

Eqs. (3.51), (3.53) and (3.54) can be solved for the three key endogenous variables,  $\tilde{c}_0$ ,  $\tilde{c}^*$  and  $\tilde{\phi}$ , as functions of the exogenous variables, including  $\alpha$ ,  $w$ ,  $w^*$ , and  $K$ .

The level of discounted lifetime utility enjoyed by a migrant under the self-finance arrangement with family support is given by:

$$\tilde{U}^{SF} = \frac{1}{1-\theta} \left[ \frac{\theta \tilde{c}_0^{1-\theta}}{\delta} (1 - e^{-\frac{\delta}{\theta} \tilde{\phi}}) + \frac{(\tilde{c}^*)^{1-\theta}}{\delta} (e^{-\delta \tilde{\phi}} - e^{-\delta T}) \right], \quad (3.55)$$

where  $\tilde{c}_0$ ,  $\tilde{c}^*$  and  $\tilde{\phi}$  are optimally chosen.

## Chapter 4

# Migration of Skilled Workers: Policy Interaction between Host and Source Countries\*

### 4.1 Introduction

Migration of skilled workers from the developing to the advanced countries has attracted considerable attention ever since Jagdish Bhagwati brought the brain-drain problem into focus in the 1970s. By recruiting skilled professionals from the developing countries, where education is heavily subsidized by the public sector, the advanced countries were widely viewed as pursuing policies detrimental to the source countries.<sup>1</sup> When migration of skilled workers

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<sup>1</sup> It is well recognized that the problem is not only fiscal in nature. The presence of skilled workers in an economy is thought to generate positive externalities at various levels, including technological, social, political and economic. If we take the example of an important sector such as health care, massive emigration of professionals can have a devastating impact on the health status of the population in the short run and a strong

is permanent, the bulk of the potential benefits stemming from public expenditures on training are lost from the perspective of the taxpayers.<sup>2</sup> When it is temporary, there is more scope for gains, especially if the returnees bring with them productive human capital accumulated while working abroad [see, e.g., Wong (1997), Dustmann (2001), Domingues Dos Santos and Postel-Vinay (2003), Meyr and Peri (2009), Dustmann et al. (2011), and Docquier and Rapoport (forthcoming)].

The vast majority of skilled migrants come from the developing and transition economies with the main poles of attraction being the U.S.A. and Canada, but also the economies of Western Europe [see Lucas (2005)]. Recent efforts to measure the magnitudes of these flows, including the works of Salt (1997), Carrington and Detragiache (1998), Docquier and Marfouk (2006), and Beine et al. (2007), reveal that the brain drain is a particularly acute problem for the relatively small developing countries. In terms of regions, island economies of the Caribbean and the Pacific, as well as countries in Central America, Sub-Saharan Africa, and South-East Asia have the highest skilled-emigration rates in proportion of their skilled populations.<sup>3</sup>

In the 21st century, emigration of skilled workers from the less developed

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negative influence on productivity and welfare in the long run.

<sup>2</sup> Note that even permanent migration can generate benefits for the source country through network effects, by developing business links at home, and through remittance flows. See, e.g., Grubel and Scott (1966), Bhagwati and Hamada (1974), McCulloch and Yellen (1977), Djajić (1986), Lopez and Schiff (1998), Rauch and Casella (2003), Kugler and Rapoport (2007), and Javorcik et al. (2011). In addition, a number of papers examine how the prospect of emigration can contribute to the accumulation of human capital in the source country by inducing individuals to invest more in their education [see, e.g., Mountford (1997), Wong (1997), Stark et al. (1997), Vidal (1998), Beine et al. (2001), Bertoli and Brücker (2011), and Mountford and Rapoport (2011)]. In an important recent study of this relationship, Beine et al. (2008) analyze data for 127 developing economies and find that doubling the emigration rate of the highly skilled induces the population of the source country to increase its human capital formation on the average by 5%.

<sup>3</sup> See Commander et al. (2004) and Docquier and Rapoport (2008) for very useful surveys of the various issues and evidence related to the brain drain.

parts of the world continues with a growing number of advanced countries offering fast-track labor-market access for skilled migrants through special temporary visa programs, such as the H1-B visa in the U.S.A. or the “Blue Card” in the EU.<sup>4</sup> In response to a severe shortage of health-care workers, Japan has entered into bilateral agreements with Indonesia, the Philippines, and Vietnam to recruit a certain number of nurses on the basis of three-year contracts.<sup>5</sup> Other countries aim to increase their stocks of highly trained workers by means of *permanent* immigration programs. The Canadian points system is a prominent example of this policy, also followed in slightly different forms by Australia, New Zealand and, more recently, Great Britain. In the U.S.A., special permanent residence visas for highly talented individuals have been available for decades.

These practices and policies clearly have an impact on the flows of highly trained migrants from the developing economies. The outflows of skilled workers reduce, in turn, the incentive for the authorities to provide public subsidies for higher education [see Justman and Thisse (1997)]. In an important recent paper, Docquier et al. (2008) examine this question both theoretically and empirically. On the basis of a sample of 108 middle-income and low-income countries they find a negative relationship between education subsidies and skilled emigration rates. An obvious consequence is that the level of training and human capital possessed by the graduates (and thus skilled emigrants) is likely to be lower than it would be otherwise. Lower skills of migrants,

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<sup>4</sup>In the case of the European Blue Card initiative, highly-skilled non-EU nationals are granted renewable 2 year work permits. In addition, a holder of such a permit, who returns back to his/her country of origin after having worked in the EU for an extended period of time, has the possibility to reenter and work in the EU in the future without going through the application procedure over again (Council Directive 2009/50/EC).

<sup>5</sup>In theory, the foreign nurses can stay longer if they pass a Japanese nursing exam within the three-year period. As fluency in the Japanese language is difficult to achieve for these foreign workers within such a limited period of time, only one Philippino and two Indonesians out of a total of 251 managed to pass the exam in 2010 (see Asahi Shimbun (2010)).

in turn, affect the relationship between the costs and benefits of immigration from the perspective of the host countries. This can and does influence their immigration policies. The points systems of Canada, Australia and New Zealand are designed to filter out those with low training and skills. In the U.S.A., whether an H1-B worker can renew her temporary three-year visa depends on the willingness of the employer to sponsor a renewal, which depends to a large extent on the worker's training and ability.

The purpose of this study is to examine the brain-drain problem within a game-theoretic framework, where both the immigration policy of the host country and the optimal provision of higher education and training in the source country are endogenously determined. The analysis is conducted in the context of a simple two-country model developed in Section 2. The host country's objective is to support the profitability of enterprises employing skilled labor while also taking into account the fiscal impact of immigration. The latter consists of the immigration-induced increase in tax revenues minus the cost of public services absorbed by the skilled immigrants and their dependents. The policy instrument at the disposal of the host country is assumed to be the duration of time it allows migrants to work in the economy. The source country is assumed to provide education free of charge to its citizens, with the objective of maximizing its net GDP. How much education is optimally provided depends on whether or not its citizens work abroad and, if they do, how long they stay.

Within this simple framework, Section 3 solves for the Nash equilibrium values of the policy instruments of both countries and examines how they respond to changes in the model's parameters. It is found that the host countries with relatively higher tax rates on income, where the authorities attach a relatively larger weight to employers' interests in their objective function, and where the public sector provides individuals with lower levels of social services, are countries that have stronger incentives to allow their skilled immigrants to work in the economy for a longer period of time. Whether a longer duration of stay raises or lowers the optimal level of training provided by the source



country depends primarily on the rate at which immigrants accumulate skills while working abroad and the valuation of those skills after return. It is also found that an increase in the cost of providing public education reduces the equilibrium level of training and the amount of time immigrants are allowed to work in the host country. An increase in the home-country valuation of skills acquired by migrant workers abroad has the opposite effects on the two policy instruments: The source country provides more training and the host country allows migrants to stay longer. Finally, if the host country chooses to increase its *stock* of immigrants, this will either lower or increase the level of training provided by the source country, depending on the parameters of the model.

Section 4 extends the analysis to a setting where both countries set their policies to maximize joint welfare. In that case the level of training provided by the source country is higher in comparison with its Nash equilibrium value, while the duration of stay of immigrants in the host country may be either higher or lower. Section 5 looks at the equilibrium with permanent migration and Section 6 concludes the paper with a summary of the main findings.

## 4.2 The Analytic Framework

We consider a world consisting of two countries: An advanced labor-importing country and a less-developed country of emigration. The latter provides higher education and training to its citizens so as to maximize its GDP, net of training costs. Because potential earnings of skilled workers are higher abroad, some of the graduates will choose to migrate and thereby contribute to the GDP of the foreign rather than the home country. Migration opportunities may be temporary or permanent, depending on immigration policy of the host country, to which we now turn.

### 4.2.1 Host Country

The authorities of the host country,  $F$ , are typically concerned with two key issues when choosing the structure of their immigration policy. One of them is the fiscal impact of immigration: While employment of immigrants increases the economy's output and revenues of the fiscal authority, immigration also implies greater absorption of services provided by the public sector. This is a particular concern in the case of low-skilled workers (especially in economies that rely heavily on foreign sources of unskilled labor), although the issue is also important in the case of skilled workers in economies with generous social programs.<sup>6</sup>

Another key issue is the impact of immigration on the distribution of income between the native workers and their employers. Immigration allows employers to enjoy larger rents by hiring foreign workers. If the demand for labor expands, immigration prevents wages of natives from rising as much as they otherwise would, serving to redistribute income from native workers (and

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<sup>6</sup> The various versions of the "points" system used in Canada, Australia and New Zealand, for example, are designed to attract skilled immigrants in the early phase of their productive lives, precisely because of the concern that their net contribution to the economy is likely to be negative if immigration takes place past a certain age. See DeVoretz and Ozsomer (1998) and DeVoretz (2001) for calculations on the net fiscal contribution of immigrants in Canada. Although immigration policies in the advanced countries have many dimensions, over the last couple of decades considerable attention has been focused on policy changes aimed at increasing the net fiscal contribution of immigrants. In addressing this issue, the 1996 Immigration Reform and Immigrant Responsibility Act in the United States has severely restricted immigrant access to means-tested social programs up until they become US citizens. In Western European countries, the conditions under which dependents of immigrants can reunite with the household head on a permanent basis have been tightened, with the effect of excluding those who are likely to become a heavy burden for the public sector. The instruments used include minimum-income and housing requirements that must be met by the sponsor. We do not model these instruments in the present study, as it would require much greater focus on the structural characteristics of immigrant households and potentially distract the reader from the main point of the paper.

immigrants) to their employers. Broadly speaking, the number of immigrants allowed to work in the economy reflects the influence that employers have in relation to native workers in shaping immigration policy.

We will not address this important domestic political-economy issue in the present study, as it has already received considerable attention. We will simply assume that the stock of immigrants,  $M$ , allowed to hold a valid work permit at any point in time is exogenously given, having been determined behind the scenes in a bargaining process involving various stakeholders in the host country.<sup>7</sup> We will focus, instead, on another key aspect of immigration policy that has not been treated in the theoretical literature on skilled-worker migration: The problem of deciding whether to admit immigrants on a permanent or temporary basis and, in the latter case, setting the optimal duration of the work permit.

With respect to the duration of stay, employers have a strong preference for having the same foreign worker over a relatively long period of time. High turnover is especially undesirable in the skilled occupations where the productivity of an employee can grow significantly with experience and on-the-job training, much of it being specific to the firm. We try to capture this in our analysis below by assuming that  $H$ , the marginal productivity of a skilled foreign worker, is an increasing function of the amount of time,  $t$ , spent on the job abroad, as well as her level of training,  $\varepsilon$ , at the time of arrival. A migrant's marginal productivity in host-country employment is thus given by  $H(\varepsilon, t)$ , where we assume  $H_\varepsilon > 0$ ,  $H_t > 0$ ,  $H_{\varepsilon\varepsilon} < 0$ ,  $H_{tt} < 0$ ,  $\lim_{\varepsilon \rightarrow \infty} H_\varepsilon = 0$ . One would also expect that  $H_{\varepsilon t} \geq 0$ .

Let the wage paid to foreign workers be a constant,  $w$ , which is lower than the marginal productivity of labor.<sup>8</sup> The average amount of rent, measured

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<sup>7</sup> The numbers of immigrants admitted to the advanced countries are typically subject to numerical quotas for various types of workers, as in the case of the H1-B visa or the European "Blue Card" program, although in other cases the numbers merely represent loose targets, as in the case of Canadian immigration policy or that of Switzerland during its post-war boom.

<sup>8</sup>In the case of skilled H1-B workers in the USA, Martin, Chen and Madamba (2000)

as a flow, enjoyed by an employer of a migrant worker is then

$$\frac{1}{\tau} \int_0^{\tau} [H(\varepsilon, t) - w] dt, \quad (4.1)$$

where  $\tau$  represents the maximum duration of the work permit provided by the authorities.<sup>9</sup> If the permit is temporary, it is not renewable, requiring the migrant to return to the source country, S, on the date of expiration. Alternatively, if F offers permanent residence to a migrant worker, we assume that the latter does not return to S.

With respect to the fiscal impact of immigration, let us suppose that all income, whether from labor or capital, is taxed at the rate  $\theta$ . The average flow of tax revenue from the output produced per migrant worker is then simply

$$\frac{1}{\tau} \int_0^{\tau} \theta H(\varepsilon, t) dt. \quad (4.2)$$

Concerning the cost of providing public services to an immigrant per unit of time, we shall assume that it amounts to a flow  $c$  if the migrant comes alone and  $(1 + a)c$  if s/he is accompanied by family members. The probability,  $\pi$ , that a migrant comes accompanied by family members, is clearly an increasing function of the expected duration of stay,  $\tau$ . The cost of providing a migrant and any accompanying dependents with public services, measured as a flow, is therefore given by  $c[1 + a\pi(\tau)]$ , where  $\pi(\tau) \in [0, 1]$  and  $a$  is likely to exceed unity.<sup>10</sup> It seems most realistic to assume that the second derivative of  $\pi(\tau)$ ,  $\pi_{\tau\tau} > 0$  for low values of  $\tau$ , but becomes negative at some point as  $\tau$  gets

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report evidence that foreign workers are paid less than the natives with comparable skills. In some economies, the underpayment of migrant workers is institutionalized. For foreign contract workers in Taiwan, the wage set by the authorities is roughly one third lower than that paid to native workers. See Stein (2003).

<sup>9</sup>As hiring low-cost foreign labor generates a rent for an employer, there is an excess demand for migrant workers. For simplicity, we assume that employers are invited to participate in the program after being chosen at random by the authorities. The wage they are permitted to pay foreign workers is assumed to be strictly regulated and set below that received by native workers.

<sup>10</sup> In a dynamic setting, immigrant children (and particularly those of skilled immigrants

closer to  $T$ , where  $T$  is the length of the migrant's planning horizon. We shall therefore posit that the function  $\pi(\tau)$  is initially increasing in a convex manner up to a certain (inflection) point after which it becomes concave.<sup>11</sup> We shall also assume that  $\lim_{\tau \rightarrow 0} \pi(\tau) = 0$  and  $\lim_{\tau \rightarrow T} \pi(\tau) = 1$ .

Let us suppose that employers' rents and the net fiscal impact of hosting  $M$  migrant workers are the two key arguments in the objective function of the immigration authorities.<sup>12</sup> In this context, the problem for F is to choose

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in ageing societies) may have a positive net impact on public-sector finances. Chojnicki et al. (2011, p.344) find that the fiscal impact of immigration has been positive for the US economy, in spite of the fact that immigrants have been on average less educated than natives. This was mainly due to their younger age and higher fertility rates relative to natives, which resulted in a higher ratio of tax payers to beneficiaries of the welfare state. This potentially positive impact of hosting dependents of immigrants is relevant for the case of permanent migration, examined in Section 5, but less so when the duration of the household head's stay in the host country is limited.

<sup>11</sup>This reflects the observation that for low values of  $\tau$ , it is not economical for a migrant to bring the family along to the host country, as the associated migration costs impose a heavy burden without necessarily generating the offsetting benefits. For a low  $\tau$  it makes more sense to leave the family in the source country, where the cost of consumption is typically lower and where the family can enjoy the continuity of residence along with a net increase in its standard of living due to higher earnings generated abroad by the household head. The vast majority of temporary migrants do in fact leave their family behind when the duration of the contract abroad is for just a year or two. For more extended stays, separation can become increasingly difficult to cope with and the advantage of avoiding migration costs and benefiting from the lower cost of family consumption at home can become small relative to the benefits of family unity. As the duration of stay abroad increases to the range of roughly 2-6 years, we would therefore expect  $\pi$  to rise quickly with  $\tau$  and family migration to become the dominant mode. Further increases in  $\tau$  can be expected to raise  $\pi$  further, but at a diminishing rate. The exact shape of the  $\pi(\tau)$  function under various conditions in the host and source countries is an empirical question on which very little systematic data is available. Since the parameter values of the function are not crucial for the theoretical analysis of this paper, we leave this issue on the agenda for future research.

<sup>12</sup>One can easily add integration costs of immigration as a separate argument. For simplicity, we prefer to consider such costs as being reflected in the values of  $c$  and  $a$ .

$\tau$  that maximizes its objective function,  $W$ , which has two components: The flow of average annual (after-tax) rents enjoyed by the employers and the average annual net fiscal impact of hosting  $M$  migrant workers:

$$W = M \left[ \frac{\lambda}{\tau} \int_0^\tau (1 - \theta)[H(\varepsilon, t) - w]dt + \frac{\theta}{\tau} \int_0^\tau H(\varepsilon, t)dt - c[1 + a\pi(\tau)] \right], \quad (4.3)$$

where  $\lambda \in (0, 1)$  is the weight attached by the government to the employers' rents, captured by the first term in the large brackets, while the net fiscal impact is represented by the difference between the last two terms. A necessary condition for the maximization of  $W$  with respect to  $\tau$  is that

$$\frac{\partial W}{\partial \tau} \equiv W_\tau = \frac{M[\lambda(1 - \theta) + \theta]}{\tau} \left[ H(\varepsilon, \tau) - \frac{1}{\tau} \int_0^\tau H(\varepsilon, t)dt \right] - Mca\pi_\tau = 0, \quad (4.4)$$

where  $H(\varepsilon, \tau)$  is the marginal productivity of a migrant worker at the moment just before she returns to the source country. Since we assumed that  $H_t > 0$ ,  $H(\varepsilon, \tau)$  is larger than the average productivity of a migrant worker,  $\frac{1}{\tau} \int_0^\tau H(\varepsilon, t)dt$ . This guarantees that the expression in the brackets of eq. (4.4) is positive. The last term captures the increase in the fiscal burden associated with the higher propensity for migrants to arrive accompanied by family members as  $\tau$  is allowed to increase. In general, there can be zero, one, two or three internal values of  $\tau$  that satisfy (4.4), given our assumptions on functions  $\pi(\tau)$  and  $H(\varepsilon, t)$ . Note that  $\tau = 0$  is never an optimum. Let us denote the vector of values of  $\tau$  which satisfy eq. (4.4) by  $\tau^0$ .

The second derivative of  $W$  with respect to  $\tau$  is given by

$$\begin{aligned} \frac{\partial W_\tau}{\partial \tau} \equiv W_{\tau\tau} &= \frac{M(\lambda(1 - \theta) + \theta)}{\tau^2} \left[ \tau H_\tau(\varepsilon, \tau) - 2H(\varepsilon, \tau) + \frac{2}{\tau} \int_0^\tau H(\varepsilon, t)dt \right] \\ &- Mca\pi_{\tau\tau}. \end{aligned} \quad (4.5)$$

The first term in (4.5) is clearly negative (see Appendix 4.7.1 for proof), while the second term can be either positive or negative, depending on whether  $\tau$

lies on the convex or concave part of  $\pi(\tau)$ . Evaluating (4.5) at  $\tau^0$  we obtain the second-order condition

$$W_{\tau\tau}|_{\tau=\tau^0} = \frac{M(\lambda(1-\theta) + \theta)}{\tau^0} H_{\tau}(\varepsilon, \tau^0) - Mca \left( \frac{2\pi_{\tau}(\tau^0)}{\tau^0} + \pi_{\tau\tau}(\tau^0) \right) \geq 0,$$

Thus, the extrema  $\tau^0$  can be either maxima or minima (local or global). For a more detailed analysis of all possible outcomes see Appendix 4.7.1. In the case of two extrema (one of which is necessarily a maximum and the other a minimum) we would also need to take into account the possibility of a corner solution  $\tau = T$ .<sup>13</sup> We examine the corner outcome in Section 5 on permanent migration, but for the moment wish to analyze a unique interior optimum such that  $W_{\tau\tau}(\tau^0) < 0$ . An analytical solution with specific functional forms is presented in Appendix B.<sup>14</sup>

## 4.2.2 Source Country

Suppose that the objective of the source country, S, is to maximize the welfare of its residents, while allowing them to have the freedom of international labor mobility. There is obviously a range of instruments available. The one we wish to focus on in the context of a model of skilled-worker migration is the level of public education and training,  $\varepsilon$ , provided to each member of the labor force. We shall assume that only the public educational system exists as liquidity-constrained households are unable to offer their children private education.

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<sup>13</sup>If  $\tau^0$  is a unique extremum and  $W_{\tau\tau}(\tau^0) < 0$ , then  $\tau^0$  is a global maximum. If there are three extrema, the first and the third are necessarily maxima, so that  $W(T)$  cannot lie above the value of  $W$  evaluated at the third extremum. Thus, a corner solution  $\tau = T$  may only occur when (a)  $W$  is monotonically increasing everywhere on  $[0, T]$ ; (b) there are two extrema; (c) when  $W$  is monotonically increasing and has an inflection point, i.e.,  $W_{\tau}(\tau^0) = 0$  and  $W_{\tau\tau}$  switches sign at  $\tau^0$ . These cases are illustrated in the figure of the Appendix 4.7.1: case (a) corresponds to Panel A on the left, case (b) to Panel B on the right, case (c) to Panel A on the right.

<sup>14</sup>Appendix B is available online at [https://edit.ethz.ch/cer/resec/people/vinogaa/Appendices\\_BCD.pdf](https://edit.ethz.ch/cer/resec/people/vinogaa/Appendices_BCD.pdf)

Moreover, all students are assumed to be of identical ability.<sup>15</sup>

Education is costly, with government expenditure per individual assumed to be  $x\varepsilon$ , where  $x$  is the constant cost of providing more  $\varepsilon$ . The benefit of education for the economy manifests itself in a higher level of output, with the marginal productivity of a worker in source-country employment given by  $H^*(\varepsilon)$  with  $H_\varepsilon^* > 0$ ,  $H_{\varepsilon\varepsilon}^* < 0$ , and  $\lim_{\varepsilon \rightarrow \infty} H_\varepsilon^* = 0$ .<sup>16</sup>

As some of the students will migrate at the time of graduation, the full benefits of the educational program are not captured by S. Some of the benefits spill over to F. This externality will obviously affect the optimal level of training provided to citizens. To define the problem in more concrete terms, let us assume that the objective of S is to maximize its steady-state GDP, net of educational expenditures. Suppose that  $L^*$  individuals are born at each instant, with their working lives being from the age of 0, when they graduate, to the age of  $T$ . The steady-state outflow of emigrants,  $M/\tau$ , is set by the immigration policy of the host country, where  $M$  is the stock of migrants and  $\tau$  is the duration of their stay abroad. Focusing here on the case of temporary migration, we may express the objective function of S as

$$W^* = (L^* - \frac{M}{\tau})TH^*(\varepsilon) + \frac{M}{\tau}(T - \tau)\phi H(\varepsilon, \tau) - xL^*\varepsilon, \quad (4.6)$$

where  $\phi \leq 1$  is the proportion of a migrant's productivity in F, just before return, that is transferrable to the labor market of S. The first term in (4.6) corresponds to the productivity of the non-migrant population, the second

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<sup>15</sup>The problem of international migration of skilled workers with heterogeneous abilities was first examined by Djajić (1989). We do not address this issue in the present study. Everyone in our model gets the same amount of education provided by the authorities and ends up with the same amount of skill when the training is completed.

<sup>16</sup>Note that we are assuming that local workers do not become more productive with experience in the source-country labor market. This is to sharpen our focus on the technological differences between countries and the possible benefits that a source country may enjoy due to return migration from a more advanced host country. None of the principal findings of the paper would change if we assumed that a worker's productivity is an increasing function of experience in the domestic labor market.



term reflects the contribution of all the returnees and the last term corresponds to the public cost of education. One can assume that the returnees bring back valuable skills acquired abroad,<sup>17</sup> so that  $\phi H(\varepsilon, \tau) > H^*(\varepsilon)$  or, at the other extreme, that the skills accumulated in F are largely firm specific and that having been away for  $\tau$  units of time actually makes returnees less productive in comparison with similarly educated non-emigrants [i.e.,  $\phi H(\varepsilon, \tau) < H^*(\varepsilon)$ ]. We shall ignore this second possibility on the grounds that it is much less likely to be empirically relevant than the first.

The source country will set  $\varepsilon$  to maximize  $W^*$ , so that

$$\frac{\partial W^*}{\partial \varepsilon} \equiv W_\varepsilon^* = (L^* - \frac{M}{\tau})TH_\varepsilon^*(\varepsilon) + \frac{M}{\tau}(T - \tau)\phi H_\varepsilon(\varepsilon, \tau) - xL^* = 0. \quad (4.7)$$

Given that  $H_\varepsilon^*$  and  $H_\varepsilon$  are both positive and monotonically declining in  $\varepsilon$ , with  $\lim_{\varepsilon \rightarrow \infty} H_\varepsilon = 0$  and  $\lim_{\varepsilon \rightarrow \infty} H_\varepsilon^* = 0$ , the extremum of  $W^*$  is unique. Let us denote it by  $\varepsilon^0$ . The second-order derivative of  $W^*$  is

$$\frac{\partial W_\varepsilon^*}{\partial \varepsilon} \equiv W_{\varepsilon\varepsilon}^* = (L^* - \frac{M}{\tau})TH_{\varepsilon\varepsilon}^*(\varepsilon)dt + \frac{M}{\tau}(T - \tau)\phi H_{\varepsilon\varepsilon}(\varepsilon, \tau)dt < 0, \quad \forall \varepsilon, \quad (4.8)$$

ensuring that  $\varepsilon^0$  is the global maximum. Rewriting (4.7) as

$$W_\varepsilon^* = L^*(TH_\varepsilon^* - x) + \frac{M}{\tau}[(T - \tau)\phi H_\varepsilon(\varepsilon, \tau) - TH_\varepsilon^*(\varepsilon)] = 0,$$

we see that if there is no migration (i.e.,  $M = 0$ ), the optimal level of training is such that,  $x$ , the marginal cost of an extra unit of education, is equal to

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<sup>17</sup>Domingues Dos Santos and Postel-Vinay (2003) explicitly look at the effect of knowledge diffusion through return-migration. In their simple model they show that temporary migrants can boost the home country's productivity level by bringing a superior technology from the host country. In the long run this may lead to lower emigration and more return migration. Their analysis, however, is focused only on the sending (i.e., developing) economy, while our model considers the interaction between the policies of both the source and host countries. Dustmann et al. (2011) build a model in which individuals possess multiple skills and show that differences in the rates of return to these skills between the host and the source country may induce migrants to return home. By contrast, in our model, there is only one type of skill. See also a recent overview of this literature in Docquier and Rapoport (forthcoming).

$TH_\varepsilon^*(\varepsilon)$ , which is the increase in the undiscounted lifetime productivity of a non-migrant.<sup>18</sup> With migration, either a higher or a lower level of training is optimal, depending on whether

$$D \equiv (T - \tau)\phi H_\varepsilon(\varepsilon, \tau) - TH_\varepsilon^*(\varepsilon) \quad (4.9)$$

is positive or negative, respectively. The second term in (4.9) corresponds to the increase in the lifetime productivity of a non-migrant due to an increase in training by one unit. The first term captures a returnee's contribution to source-country output due to the same extra unit of training provided before emigration. If an additional unit of training results in an increase in the productivity of a returnee relative to that of a non-migrant in excess of  $T/(T - \tau)$ , then  $D > 0$ . In that case S benefits more by offering extra training to a worker who migrates temporarily than it does by offering it to another who remains at home. In consequence, it pays to provide more public education to citizens in a regime of temporary emigration than it does under autarky. Alternatively, if the skills accumulated in F are not easily transferrable to S (which might be due to a difference in the levels of development of the two countries) and/or  $(T - \tau)/T$  is not sufficiently large,  $D < 0$ . It is then optimal to provide less training in the context of an open economy than it is under autarky. We shall consider both possibilities in the analysis below.<sup>19</sup>

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<sup>18</sup> Discounting the future benefits of public education would slightly complicate the notation. In terms of its impact on our findings, in an autarky equilibrium it would result in a lower  $\varepsilon$ , while in the case of temporary migration, with the benefits of education of those who migrate being deferred still further out in time, the effect on  $\varepsilon$  is even stronger. For formal treatment, see Appendix C, available online at [https://edit.ethz.ch/cer/resec/people/vinograa/Appendices\\_BCD.pdf](https://edit.ethz.ch/cer/resec/people/vinograa/Appendices_BCD.pdf).

<sup>19</sup> In a related paper, Wong and Yip (1999) consider an overlapping generations model of skilled migration, education, and endogenous growth. Emigration of skilled workers in their model lowers the growth rate of the economy, which in turn calls for greater expenditure on education by the authorities whose objective is to maintain the growth rate. The difference in the policy response to emigration of skilled workers in our model stems from the difference in the assumed policy objective.

### 4.3 Nash Equilibrium with Temporary Migration

Eqs. (4.4) and (4.7) are the reaction functions of F and S, respectively. The partial derivative of (4.4) with respect to  $\varepsilon$  is given by

$$\frac{\partial W_\tau}{\partial \varepsilon} \equiv W_{\tau\varepsilon} = M \left\{ \frac{(\lambda(1-\theta) + \theta)}{\tau} \left[ H_\varepsilon(\varepsilon, \tau) - \frac{1}{\tau} \int_0^\tau H_\varepsilon(\varepsilon, t) dt \right] \right\} > 0. \quad (4.10)$$

The sign of  $W_{\tau\varepsilon}$  is positive because we assumed that  $H_{\varepsilon t} \geq 0$ , so that  $H_\varepsilon$  evaluated at  $t = \tau$  is greater than the average of  $H_\varepsilon$  for  $t \in [0, \tau]$ . Since  $W_{\tau\tau} < 0$  in the neighborhood of an internal solution for  $\tau$ , the slope of the host country's reaction function,  $RR$ , is positive (i.e.,  $d\tau/d\varepsilon|_{W_\tau=0} = -W_{\tau\varepsilon}/W_{\tau\tau} > 0$ ).

Differentiating the source-country reaction function (4.7) with respect to  $\tau$  we obtain

$$\frac{\partial W_\varepsilon^*}{\partial \tau} \equiv W_{\varepsilon\tau}^* = \frac{MD}{\tau^2} (\xi_{D\tau} - 1), \quad (4.11)$$

where  $D$  is defined in (4.9) and the elasticity of  $D$  with respect to  $\tau$ ,  $\xi_{D\tau} \equiv \frac{\partial D}{\partial \tau} \frac{\tau}{D} \geq 0$ . The slope of the reaction function  $R^*R^*$  of country S is given by  $d\tau/d\varepsilon|_{W_\varepsilon^*=0} = -W_{\varepsilon\varepsilon}^*/W_{\varepsilon\tau}^*$ . Since  $W_{\varepsilon\varepsilon}^* < 0$ , the sign of the slope is the same as that of  $W_{\varepsilon\tau}^*$  in eq. (4.11). It is therefore important to examine more closely the expression for  $W_{\varepsilon\tau}^*$ , which effectively determines whether it is optimal for S to increase or decrease spending on the training of its citizens in response to an increase in the value of  $\tau$  chosen by country F. On the basis of (4.11), we observe that the slope of  $R^*R^*$  is positive in two cases. First, when  $D > 0$  and  $\xi_{D\tau} > 1$ . A positive  $D$  means that the marginal effect of an extra unit of training on the productivity of a returnee exceeds the effect on the lifetime productivity of a non-migrant, i.e., there is a positive gap between these two marginal effects. The benefit of providing more  $\varepsilon$  is then larger for S, the greater the flow of migrants (and therefore returnees). An increase in  $\tau$  reduces this flow in the same proportion because the stock of migrants,  $M$ ,

is held constant by F. This obviously calls for a reduction in  $\varepsilon$ . However, if  $\xi_{D\tau} > 1$ , the positive gap between the productivity of a returnee and a non-migrant expands *more* than in proportion to  $\tau$ .<sup>20</sup> It then pays for S to raise  $\varepsilon$  in response to an increase in  $\tau$  in spite of the associated reduction in the flow of returnees.  $R^*R^*$  is therefore positively sloped.

The second case in which the slope of  $R^*R^*$  is positive occurs when  $D < 0$  and  $\xi_{D\tau} < 1$ . When  $D < 0$ , the benefit of providing more education to its citizens is larger for S, the *smaller* the flow of migrants. If, in addition,  $\xi_{D\tau} < 1$ , the reduction in the outflow of skilled workers due to an increase in  $\tau$  has a more significant impact than any associated improvement in  $D$ . It is then beneficial, once again, for S to raise  $\varepsilon$  in response to a higher  $\tau$ . In all other cases it is optimal for S to reduce the provision of public education in reaction to an increase in  $\tau$  and hence  $R^*R^*$  is negatively sloped.

Figures 4.1 and 4.2 illustrate the determination of  $\tau$  and  $\varepsilon$  in the Nash equilibrium. Figure 4.1 is drawn for the case  $W_{\varepsilon\tau}^* < 0$  (negatively sloped  $R^*R^*$ ) and Figure 4.2 for the case  $W_{\varepsilon\tau}^* > 0$  (positively sloped  $R^*R^*$ ). The host country's reaction function  $RR$  is positively sloped in both figures. Stability of the equilibrium requires that

$$\Delta \equiv W_{\tau\tau}W_{\varepsilon\varepsilon}^* - W_{\tau\varepsilon}W_{\varepsilon\tau}^* > 0,$$

which implies that if  $R^*R^*$  is positively sloped, it must be steeper than  $RR$ , as illustrated in Figure 4.2. We shall assume this to be the case.

FIGURES 1 AND 2 – POSITIONED HERE, SIDE BY SIDE

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<sup>20</sup> In general, an increase in  $\tau$  has two effects on the gap. On the one hand, it reduces the time that a returnee spends back home ( $T - \tau$  falls) and thus reduces her lifetime contribution to the GDP of S. On the other hand, it raises a migrant's marginal return to training ( $H_{\varepsilon\tau} > 0$ ).

### 4.3.1 Comparative Statics

To examine the implications of changes in the key exogenous variables on the Nash-equilibrium values of the two policy instruments, we differentiate totally the reaction functions (4.4) and (4.7) to obtain

$$\begin{bmatrix} W_{\tau\tau} & W_{\tau\varepsilon} \\ W_{\varepsilon\tau}^* & W_{\varepsilon\varepsilon}^* \end{bmatrix} \begin{bmatrix} d\tau \\ d\varepsilon \end{bmatrix} = \begin{bmatrix} -W_{\tau\theta}d\theta - W_{\tau c}dc - W_{\tau\lambda}d\lambda \\ -W_{\varepsilon x}^*dx - W_{\varepsilon\phi}^*d\phi - W_{\varepsilon M}^*dM \end{bmatrix},$$

which enables us to solve for the effects of changes in the exogenous variables  $\theta, c, \lambda, \phi, x$ , and  $M$  on the equilibrium values of  $\tau$  and  $\varepsilon$ . The results are presented in the following subsections.

### 4.3.2 Increase in the Tax Rate in Country F

An increase in the tax rate,  $\theta$ , of the host country has the following implications:

$$\Delta \frac{d\tau}{d\theta} = -W_{\tau\theta}W_{\varepsilon\varepsilon}^* > 0, \quad (4.12)$$

where  $W_{\tau\theta} = M \frac{(1-\lambda)}{\tau} \{H(\varepsilon, \tau) - \frac{1}{\tau} \int_0^\tau H(\varepsilon, t)dt\} > 0$ . It follows that a higher  $\theta$  increases the Nash-equilibrium value of  $\tau$ . Host countries with higher tax rates on earnings (including employer rents) can therefore be expected to allow skilled immigrants to stay longer. As we have assumed that the stock of migrants,  $M$ , is held constant, this comes at the expense of a smaller inflow of foreign workers.

The effect of a higher tax rate on the Nash equilibrium amount of training provided by country S is ambiguous and depends on the sign of  $W_{\varepsilon\tau}^*$ .

$$\Delta \frac{d\varepsilon}{d\theta} = W_{\tau\theta}W_{\varepsilon\tau}^* \gtrless 0. \quad (4.13)$$

If  $W_{\varepsilon\tau}^* < 0$ , an increase in the tax rate lowers the amount of training, as that is the optimal response of S to a rise in  $\tau$ . In terms of Figure 4.1, an

increase in  $\theta$  shifts the  $RR$  schedule up and to the left (shown by the dashed line  $R'R'$ ), causing it to intersect the unaffected  $R^*R^*$  locus at a lower value of  $\varepsilon$ . Alternatively, if  $W_{\varepsilon\tau}^* > 0$ , we have the case depicted in Figure 4.2, with an upward shift of  $RR$  giving rise to an increase in  $\varepsilon$ . This reflects the fact that when  $W_{\varepsilon\tau}^* > 0$ , an increase in each migrant's duration of stay abroad (along with a proportional reduction in the flow of returnees) actually raises the source-country benefit of training relative to the cost, making an increase in  $\varepsilon$  optimal.

### 4.3.3 Higher Cost of Public Services Absorbed by Immigrants

Consider next the implications of an increase in  $c$ , the cost of public services provided to immigrants:

$$\Delta \frac{d\tau}{dc} = -W_{\tau c} W_{\varepsilon\varepsilon}^* < 0, \quad (4.14)$$

$$\Delta \frac{d\varepsilon}{dc} = W_{\tau c} W_{\varepsilon\tau}^* \gtrless 0, \quad (4.15)$$

where  $W_{\tau c} = -aM\pi_\tau < 0$ . With an increase in  $c$ , the Nash-equilibrium duration of stay decreases. This stems from the assumption that if immigrants stay for a shorter period of time, they are less likely to bring with them their families that absorb costly public services. Thus, the more the public sector spends per unit of services provided to immigrants, the lower the value of  $\tau$ . Host countries with highly developed welfare systems, particularly when it comes to services provided to dependent members of an immigrant household, can thus be expected to favor relatively shorter durations of stay.

The amount of training provided by the source country to its citizens either increases or decreases, depending on whether  $W_{\varepsilon\tau}^*$  is positive or negative. The intuition here is the same as that in the previous subsection. The source country increases or cuts  $\varepsilon$  in response to a reduction in  $\tau$ , depending on whether  $W_{\varepsilon\tau}^*$  is negative or positive.

In the context of a somewhat richer model where the cost of providing public services to immigrants is a function of their education and skills, one might think of  $c$  as being a decreasing (possibly convex) function of  $\varepsilon$ . This modification of the model would not affect the qualitative results of our paper, but it would make the slope of  $RR$  steeper as the expression for  $W_{\tau\varepsilon}$  would have an additional positive term,  $-c'(\varepsilon)[1 + a\pi(\tau)] > 0$ , where  $c'(\varepsilon) < 0$ .

#### 4.3.4 Increase in the Weight of Employers' Rents

If the rents of host-country employers are assigned a larger weight,  $\lambda$ , in the objective function of country F, we have the following implications for the Nash-equilibrium values of  $\tau$  and  $\varepsilon$ .

$$\Delta \frac{d\tau}{d\lambda} = -W_{\tau\lambda}W_{\varepsilon\varepsilon}^* > 0, \quad (4.16)$$

$$\Delta \frac{d\varepsilon}{d\lambda} = W_{\tau\lambda}W_{\varepsilon\tau}^* \geq 0, \quad (4.17)$$

where  $W_{\tau\lambda} = M \frac{(1-\theta)}{\tau} \{H(\varepsilon, \tau) - \frac{1}{\tau} \int_0^\tau H(\varepsilon, t) dt\} > 0$ . A rise in  $\lambda$  therefore increases the Nash-equilibrium duration of stay while having an effect on  $\varepsilon$  that depends, once again, on the sign of  $W_{\varepsilon\tau}^*$ . This is precisely the same result that we had for an increase in  $\theta$  and the same intuition follows.

#### 4.3.5 Higher Transferability of Skills Acquired Abroad

An increase in  $\phi$  has the following effects:

$$\Delta \frac{d\tau}{d\phi} = W_{\tau\varepsilon}W_{\varepsilon\phi}^* > 0, \quad (4.18)$$

$$\Delta \frac{d\varepsilon}{d\phi} = -W_{\tau\tau}W_{\varepsilon\phi}^* > 0, \quad (4.19)$$

where  $W_{\varepsilon\phi}^* = \frac{M}{\tau}(T-\tau)H_\varepsilon(\varepsilon, \tau) > 0$ . Greater source-country valuation of skills acquired by migrants in F increases the Nash-equilibrium amount of training

and the duration of stay. If immigrants are effectively more productive at the point of return, it is then optimal for S to increase the amount of training it provides to all its citizens and for F to hold on to its skilled immigrants longer. This analysis suggests that over time, as source countries develop greater capacity to utilize the skills brought back by the returnees, the Nash-equilibrium values of  $\varepsilon$  and  $\tau$  will tend to increase.

### 4.3.6 Increase in the Cost of Training

An increase in  $x$  is found to lower the Nash-equilibrium values of both  $\varepsilon$  and  $\tau$ :

$$\Delta \frac{d\tau}{dx} = W_{\tau\varepsilon} W_{\varepsilon x}^* < 0, \quad (4.20)$$

$$\Delta \frac{d\varepsilon}{dx} = -W_{\tau\tau} W_{\varepsilon x}^* < 0, \quad (4.21)$$

where  $W_{\varepsilon x}^* = -L^* < 0$ . If there is an increase in the cost of training in country S, it no longer pays to provide as much of it as when the cost was lower. The optimal response of the host country is to cut the duration of stay of its skilled immigrants. In terms of Figures 4.1 and 4.2, an increase in  $x$  shifts the  $R^*R^*$  schedule to the left to intersect the unaffected  $RR$  locus at lower values of both  $\varepsilon$  and  $\tau$ .

### 4.3.7 Increase in the Stock of Immigrants

Consider next a shift in immigration policy of country F that results in a larger desired stock of migrants,  $M$ , employed in the economy at any point in time. We have

$$\Delta \frac{d\tau}{dM} = W_{\tau\varepsilon} W_{\varepsilon M}^* \geq 0, \quad (4.22)$$



$$\Delta \frac{d\varepsilon}{dM} = -W_{\tau\tau}W_{\varepsilon M}^* \geq 0, \quad (4.23)$$

where  $W_{\varepsilon M}^* = \frac{D}{\tau} \geq 0 \Leftrightarrow D \geq 0$ , with  $D$  defined in (4.9). Since  $W_{\tau\varepsilon} > 0$  and  $W_{\tau\tau} < 0$ , the Nash equilibrium values of  $\tau$  and  $\varepsilon$  move in the same direction. They both decline if it is optimal for S to cut  $\varepsilon$  when its borders open up to temporary migration (i.e.,  $D < 0$ ) and increase when temporary emigration triggers an increase in  $\varepsilon$  (i.e.,  $D > 0$ ). The optimal response of country F is to shorten  $\tau$  when training is reduced and to increase it when immigrants arrive with more skills.

## 4.4 Maximization of Joint Welfare

In this section we consider the case where country F chooses the duration of stay and country S chooses the amount of training to maximize joint welfare. The value of  $\tau$  must then be set such that

$$\gamma W_\tau + (1 - \gamma)W_\tau^* = 0. \quad (4.24)$$

The parameter  $\gamma \in (0, 1)$  is the relative weight attached to the welfare of F and may be interpreted to reflect its bargaining power.

Differentiating the welfare function of country S with respect to  $\tau$  yields

$$W_\tau^* = \frac{M}{\tau^2} [TH^*(\varepsilon) - \phi(T - \tau)H(\varepsilon, \tau)] + \frac{M(T - \tau)\phi H(\varepsilon, \tau)}{\tau^2} \left[ \eta_{H\tau} - \frac{\tau}{T - \tau} \right], \quad (4.25)$$

where  $\eta_{H\tau} \equiv \frac{\partial H}{\partial \tau} \frac{\tau}{H}$ . We can think of an increase in  $\tau$  as having two effects on the welfare of S, represented by the two terms in eq. (25). First, for a given stock of migrants, an increase in  $\tau$  implies a proportional reduction in the flow. More skilled workers therefore remain at home out of any generation of graduates, each contributing  $TH^*(\varepsilon)$  to GDP of S. There is, however, a correspondingly smaller return flow of migrants, which implies a GDP loss

amounting to  $\phi(T - \tau)H(\varepsilon, \tau)$  units of output per returnee. If  $TH^*(\varepsilon)$  is greater (smaller) than  $\phi(T - \tau)H(\varepsilon, \tau)$ , S experiences brain drain (gain) as a result of temporary emigration. A reduction in the flow of emigrants, due to an increase in  $\tau$ , then benefits (harms) S, contributing to  $W_\tau^*$  being positive (negative).

Second, with an increase in  $\tau$ , each migrant stays abroad longer, accumulates skills, and returns to S with a higher productivity, albeit for a shorter period of time. This effect is captured by the second term in (25). If the elasticity of  $H(.,.)$  with respect to  $\tau$ ,  $\eta_{H\tau} > \tau/(T - \tau)$ , an increase in  $\tau$  contributes positively to source-country welfare through this channel. Such an outcome is likely to emerge in a migration regime where F allows migrants to stay for only a short period of time. For relatively high values of  $\tau$ , we would expect this second term in (25) to be negative.

In summary, taking into account both effects in (4.25),  $W_\tau^*$  can be either positive or negative. The sign is unambiguously positive if S experiences a brain drain and migrants stay abroad for a relatively short period of time. Since  $W_\tau = 0$  in the Nash equilibrium,  $W_\tau^* > 0$  implies that joint welfare maximization calls for a relatively longer duration of stay for migrants in country F. Alternatively, if  $W_\tau^* < 0$ , joint welfare maximization results in a lower value of  $\tau$  when compared with Nash.

Similarly, if country S chooses  $\varepsilon$  in order to maximize joint welfare of S and F, then

$$\gamma W_\varepsilon + (1 - \gamma)W_\varepsilon^* = 0. \quad (4.26)$$

Differentiating the welfare function of country F with respect to  $\varepsilon$ , we find that

$$W_\varepsilon = M \frac{(\lambda(1 - \theta) + \theta)}{\tau} \int_0^\tau H_\varepsilon(\varepsilon, t) dt > 0. \quad (4.27)$$

Since  $W_\varepsilon^* = 0$  in the Nash equilibrium, joint welfare maximization requires a higher value of  $\varepsilon$  than the one that emerges in a non-cooperative setting.

In summary, maximization of joint welfare results in more training of workers by S and a longer or shorter duration of stay of skilled immigrants in F (depending on the sign of  $W_\tau^*$ ), when compared with the Nash-equilibrium values of these policy instruments. Note, in addition, that an increase in the bargaining power of F relative to that of S, as measured by  $\gamma$ , results in a higher  $\varepsilon$  and a shorter  $\tau$  when  $W_\tau^* > 0$  and a longer  $\tau$  when  $W_\tau^* < 0$ . Moreover, maximization of joint welfare does not necessarily give rise to an increase in the individual level of welfare of both countries. Consider for example the case where  $W_\tau^*$  is zero or close to zero. The duration of stay is then approximately the same with joint welfare maximization as it is at Nash, while the amount of training is higher. This means that the welfare of S is necessarily lower with joint welfare maximization than it is in the Nash equilibrium, while the welfare of F is unambiguously higher. In this case S has no incentive to cooperate and some side payment is needed in order to induce it to do so. A similar transfer mechanism might be necessary in order to induce S to cooperate in a situation where it is optimal for F to set  $\tau = T$ . This is the case of permanent immigration which we examine next.

## 4.5 Permanent Migration

Under certain conditions it is optimal for F to set  $\tau = T$ , i.e., invite skilled migrants to settle permanently. This corner solution may arise when (a)  $\partial W/\partial \tau = 0$  has a unique root but is positive for all other values of  $\tau$ , i.e., the objective function of F has an inflection point but is positively sloped everywhere else (see, e.g., Panel A on the right in Appendix 4.7.1), or (b)  $\partial W/\partial \tau = 0$  has two roots, the second of which is a (local) minimum (see Panel B on the right or Panel C on the left), or (c) the objective function  $W$  is positively sloped for all  $\tau \in [0, T]$  (Panel A on the left). Case (c) requires no further discussion but in the other two cases it is possible that  $W(\tau^0) < W(T)$ . Evaluating the host country's objective (4.3) at  $\tau^0$  and  $T$ ,

we get

$$W(\tau^0) = M \left\{ \frac{\lambda(1-\theta) + \theta}{\tau^0} \int_0^{\tau^0} H(\varepsilon, t) dt - \lambda w - c [1 + a\pi(\tau^0)] \right\}, \quad (4.28)$$

$$W(T) = M \left\{ \frac{\lambda(1-\theta) + \theta}{T} \int_0^T H(\varepsilon, t) dt - \lambda w - c [1 + a] \right\}, \quad (4.29)$$

where we used the fact that  $\lim_{\tau \rightarrow T} \pi(\tau) = 1$ . Subtracting (4.28) from (4.29), we find that the corner solution occurs when

$$[\lambda(1-\theta) + \theta] \left[ \frac{1}{T} \int_0^T H(\varepsilon, t) dt - \frac{1}{\tau^0} \int_0^{\tau^0} H(\varepsilon, t) dt \right] - ca[1 - \pi(\tau^0)] > 0.$$

That is, when the benefits of F stemming from the gain in a migrant's productivity (associated with the extension of the permit from  $\tau^0$  to  $T$ ) more than compensate for the additional cost of public services provided to the immigrant household.

If migration is permanent, F simply retains a stock  $M$  of permanent immigrants, with a steady-state inflow of  $M/T$  skilled migrants filling the jobs of the retiring ones. The structure of the problem is then much simpler than in the case of temporary migration as  $\tau$  is set at its maximum value of  $T$ . For S, the problem in this setting is to maximize

$$W^* = (L^*T - M)H^*(\varepsilon) - xL^*\varepsilon, \quad (4.30)$$

with respect to  $\varepsilon$ . This yields

$$\frac{\partial W^*}{\partial \varepsilon} = \left( \frac{L^*T - M}{L^*T} \right) TH_\varepsilon^*(\varepsilon) - x = 0, \quad (4.31)$$

which implies that the marginal cost of training must be equated to the product of the increase in the lifetime productivity of a non-migrant due to the extra unit of training and the proportion of graduates that remain at home. Comparing (4.31) with (4.7), we conclude that the optimal level of  $\varepsilon$  with permanent migration is unambiguously lower than that with temporary migration. Moreover, as the marginal productivity of training is assumed to be diminishing, it follows that the larger the stock of skilled migrants recruited on a permanent basis by F, the lower the optimal level of  $\varepsilon$  provided by S.

## 4.6 Conclusions

The vast literature on migration of skilled workers and the brain drain does not provide an analysis of the optimal interaction between immigration policy of the host country and the provision of public education in the source country. The present study attempts to fill this gap by developing a simple two-country model of skilled-worker migration where the host country chooses the optimal duration of stay of skilled migrants and the source country sets the level of training provided to its citizens.

In our analysis of the Nash equilibrium with temporary migration, we find that host countries that have relatively higher tax rates on incomes, that attribute a larger weight to employers' rents in their objective function, and that provide lower levels of public services to individuals, have a greater incentive to allow their skilled immigrants to work in the economy for a relatively longer period of time, including permanently. When a temporary immigration policy is chosen by the host country, the optimal level of training provided by the source country depends on the rate at which immigrants accumulate skills while working abroad and the valuation of those skills after return. Should the skills acquired abroad become more valuable in the labor market at home, it is optimal for the source country to provide a higher level of training to the workers. More training is also called for in response to a reduction in its cost. Finally, if the host country chooses to increase its *stock* of immigrants, this will lower (increase) the level of training provided by the source country if migration reduces (increases) its benefits from such training. This depends, in turn, on the rate at which migrants accumulate skills in the foreign country, the transferability of such skills to the labor market of the source country and the duration of each migrant's stay abroad. We also examine the implications of both countries acting to maximize joint welfare. The level of education provided to citizens of the source country is then greater, while the maximum duration of stay of migrant workers in

the host country may be longer or shorter when compared with the Nash-equilibrium values of these instruments.

Our model can be extended to include the analysis of several host countries/regions that compete for skilled workers from a single source country/region. This problem would be more challenging and more interesting to consider in a setting where source-country workers differ in terms of their skills and host countries differ in terms of their technology. Moreover, in contrast with our simple model with infinitely elastic supply of migrants, host countries would have to make an effort to meet their immigration quotas. This implies that the stock of migrants becomes a key endogenous variable in their objective functions. To attract foreign workers, they would need to make compromises with respect to other objectives. We would expect this to be reflected in more favorable conditions being offered to migrants: conditions with respect to the duration of stay (i.e., longer  $\tau$ ), compensation ( $w$ ), and even tax treatment, as we already observe in numerous advanced countries [See SOPEMI (2005, pp. 132-133)]. The optimal response of the source country is likely to be a cut in public expenditure on education below the level obtained under Nash equilibrium with a single host country.

There are a number of other directions in which the present model may be extended. In some cases this would complicate the analysis considerably, requiring simplifications in other dimensions. For example, our model has only one sector employing skilled labor with the authorities providing education to the entire labor force. A richer framework would consist of a two-sector economy, with one sector requiring skilled labor and the other unskilled labor. The size of the two sectors and the pattern of international trade in goods would then depend on the immigration and educational policies of the host and source countries, respectively. Second, as in Djajić (1989), one may look at the implications of emigration of skilled workers when individuals have heterogeneous abilities. In such a world, the workers with the highest abilities will likely be offered the strongest incentives to migrate, which in most modelling scenarios will accentuate the brain-drain effect for any given

stock of migrants admitted abroad. These and other possible extensions of our model would contribute significantly to our understanding of the interaction between the optimal immigration and education policies of the host and source countries in a world where international mobility of skilled labor is becoming increasingly important.

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## 4.7 Appendix

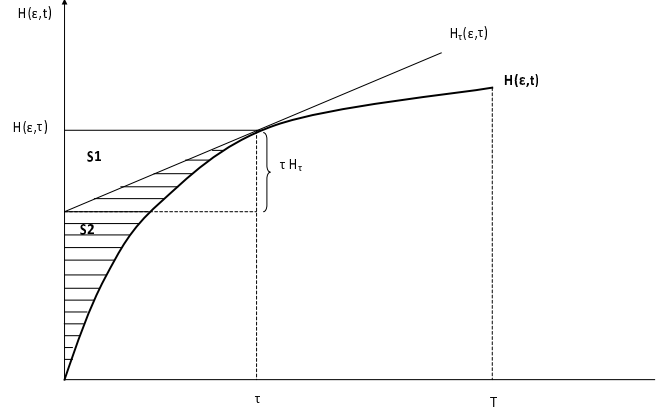
### 4.7.1 Appendix to Section 2.1

#### Second Derivative of the Host Country's Objective

To see that the first term in (4.5) is negative, multiply the term in the square brackets by  $\tau$  to get

$$\tau^2 H_\tau(\varepsilon, \tau) - 2 \left[ \tau H(\varepsilon, \tau) - \int_0^\tau H(\varepsilon, t) dt \right].$$

Note that the expression in the square brackets above is equal to the sum of the area marked by  $S_1$  and the shaded area  $S_2$  in the figure below.



Then write

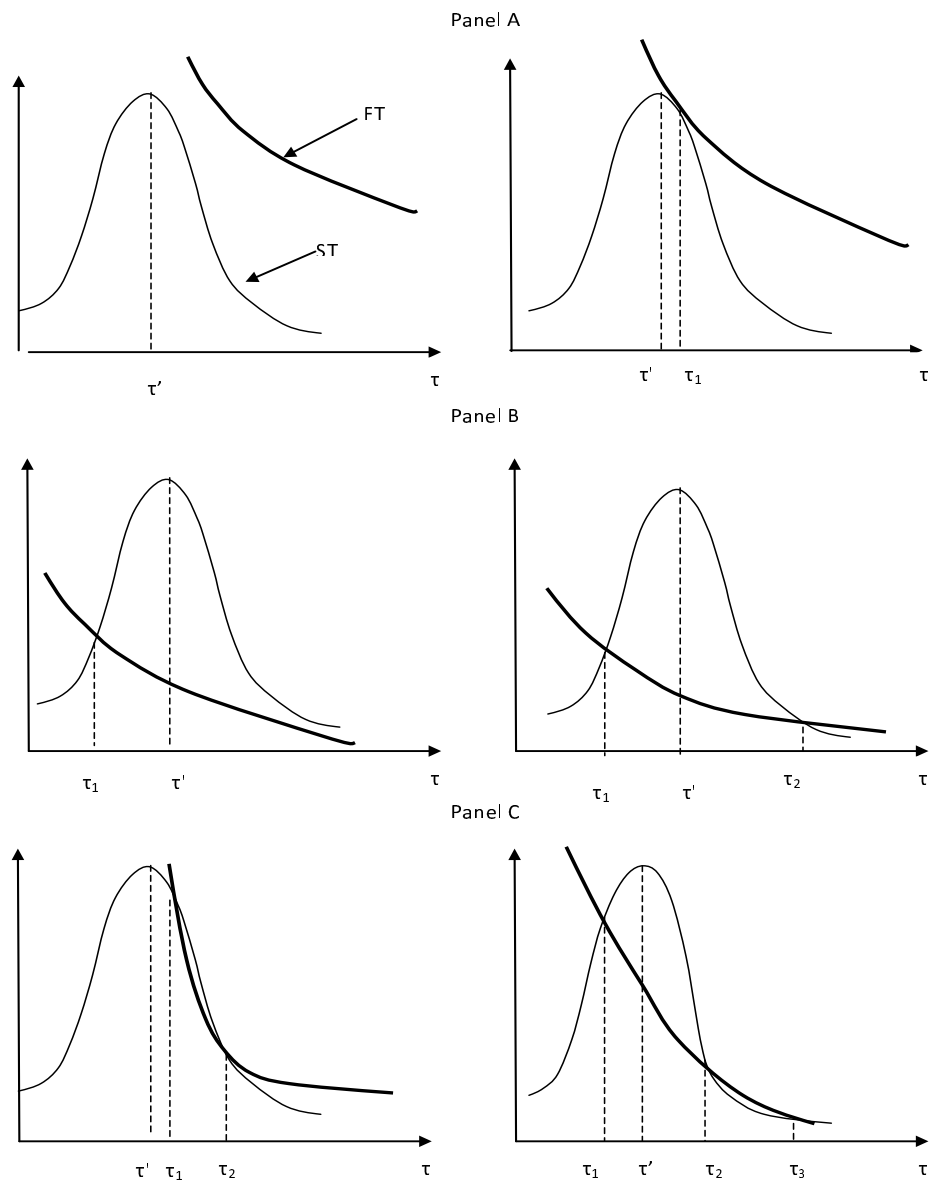
$$\begin{aligned} \tau^2 H_\tau(\varepsilon, \tau) - 2 \left[ \tau H(\varepsilon, \tau) - \int_0^\tau H(\varepsilon, t) dt \right] &= \\ &= \tau^2 H_\tau(\varepsilon, \tau) - 2(S_1 + S_2) < \tau^2 H_\tau(\varepsilon, \tau) - 2S_1 = 0, \end{aligned}$$

where the last equality follows from the fact that  $S_1 = \tau^2 H_\tau(\varepsilon, \tau)/2$ . Thus, the term in the brackets in (4.5) is unambiguously negative.

### Optimal duration of the work permit

The first term (FT) in (4.4),  $\frac{M[\lambda(1-\theta)+\theta]}{\tau} [H(\varepsilon, \tau) - \frac{1}{\tau} \int_0^\tau H(\varepsilon, t) dt]$ , is positive and monotonically decreasing in  $\tau$ , since, it's derivative with respect to  $\tau$ , i.e., the first term in (4.5), is negative (proof in Appendix 4.7.1). The second term (ST) in (4.4),  $Mca\pi_\tau$ , has a bell shape, with the maximum at the inflection point of  $\pi(\tau)$ , at  $\tau = \tau'$  (see the figure below). The case with no interior solution corresponds to  $W_\tau > 0, \forall \tau$ , so that the downward-sloping bold curve (labelled FT in the left half of Panel A) lies everywhere above the bell-shaped curve (labelled ST). It is then optimal for the host country to offer skilled migrants permanent residence. This corner solution is examined in Section 5.

The case of one optimum occurs if the downward-sloping FT curve just touches the ST curve, as shown on the right side of Panel A. This extremum cannot be a maximum, however, but rather an inflection point of  $W(\tau)$ , since the second derivative,  $W_{\tau\tau}$ , changes sign after passing through this point. A unique extremum may also occur if the FT curve crosses the ST curve from above and then lies everywhere below the decreasing portion of ST (see left side of Panel B, where the equilibrium is shown to occur to the left of the inflection point at  $\tau = \tau'$ ). In this case, we have a global maximum. An extremum may also occur to the right of the inflexion point, on the downward-sloping portion of ST). Another possible case of two extrema is illustrated in Panel C on the left. Finally, three extrema may also occur, as shown in Panel C on the right. Among all these possible solutions we are interested only in maxima, that is, those which occur when FT crosses ST from above. In case of multiple maxima, as for example those at  $\tau_1$  and  $\tau_3$  in Panel C on the right, we cannot distinguish a local maximum from the global one without assuming specific functional forms.



## 4.8 Appendix B: Example with Explicit Solution

### 4.8.1 B.1: Host country

Let  $H(\varepsilon, t) = \mu \varepsilon^\alpha t^\beta$  and  $\pi = (\tau/T)^\nu$ , where  $\mu > 0$ ,  $\alpha \in (0, 1)$ ,  $\beta \in (0, 1)$ , and  $\nu > 1$ .<sup>21</sup> Then the first-order condition for the host country's choice of  $\tau$ , eq. (4), can be written as

$$\frac{M[\lambda(1-\theta) + \theta]}{\tau} \left[ \mu \varepsilon^\alpha \tau^\beta - \frac{1}{\tau} \int_0^\tau \mu \varepsilon^\alpha t^\beta dt \right] = M c a \nu \tau^{\nu-1} T^{-\nu},$$

from which we obtain the reaction function of F

$$\tau^0 = \left[ \frac{\mu \varepsilon^\alpha \beta [\lambda(1-\theta) + \theta] T^\nu}{(1+\beta) c a \nu} \right]^{\frac{1}{\nu-\beta}}, \quad (4.32)$$

It is positively sloped since  $\nu - \beta > 0$ . The second-order condition is automatically satisfied since  $\pi(\tau)$  is convex when  $\nu > 1$ , as assumed here. The objective, for any given level of  $\varepsilon$ , is

$$W = (\mu \varepsilon^\alpha)^{\frac{\nu}{\nu-\beta}} \left[ \frac{\beta [\lambda(1-\theta) + \theta] T^\nu}{(1+\beta) c a \nu} \right]^{\frac{\beta}{\nu-\beta}}$$

### 4.8.2 B.2: Source country

Let  $H^* = \mu^* \varepsilon^\alpha$ . Then the optimal  $\varepsilon$  is set such that

$$(L^* - \frac{M}{\tau}) T \mu^* \alpha \varepsilon^{\alpha-1} + \frac{M}{\tau} (T - \tau) \phi \mu \alpha \varepsilon^{\alpha-1} (\tau)^\beta - x L^* = 0,$$

from which we obtain the reaction function of S

$$\varepsilon^0 = \left[ \frac{(L^* - \frac{M}{\tau}) T \mu^* + \frac{M}{\tau} (T - \tau) \phi \mu (\tau)^\beta}{\alpha x L^*} \right]^{\frac{1}{1-\alpha}}, \quad (4.33)$$

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<sup>21</sup>Although a convex  $\pi$  function offers a convenient way of presenting the internal solution and comparing it with the corner solution, there is little evidence that it corresponds to the most realistic form of the relationship between the migrants' expected duration of stay abroad and the probability of bringing the family along.

which is the global maximum (for a given  $\tau$ ) since the second-order condition is satisfied for any  $\varepsilon$ .

The objective, for any given  $\tau$ , is

$$W^* = \mu^* \left[ \frac{(L^* - \frac{M}{\tau})T\mu^* + \frac{M}{\tau}(T - \tau)\phi\mu(\tau)^\beta}{\alpha x L^*} \right]^{\frac{\alpha}{1-\alpha}}$$

The system of equations (4.32) - (4.33) can be solved for the Nash-equilibrium values of  $\tau$  and  $\varepsilon$ .

## 4.9 Appendix C: Effect of Discounting in Section 2.2

If we introduce discounting at the rate  $\rho$ , the source-country's objective is modified as follows

$$\max_{\varepsilon} \left( L^* - \frac{M}{\tau} \right) \int_0^T H^*(\varepsilon) e^{-\rho t} dt + \frac{M}{\tau} \int_{\tau}^T \phi H(\varepsilon, \tau) e^{-\rho t} dt - x L^* \varepsilon.$$

The first-order condition is then

$$W_{\varepsilon}^* = \left( L^* - \frac{M}{\tau} \right) H_{\varepsilon}^*(\varepsilon) \frac{1 - e^{-\rho T}}{\rho} + \frac{M}{\tau} \phi H_{\varepsilon}(\varepsilon, \tau) \frac{e^{-\rho \tau} - e^{-\rho T}}{\rho} - x L^* = 0. \quad (4.34)$$

Given that  $\frac{1 - e^{-\rho T}}{\rho} < T$  and  $\frac{e^{-\rho \tau} - e^{-\rho T}}{\rho} < (T - \tau)$ , the first two terms are smaller than the corresponding terms in (7). This implies that the effect of discounting is to lower the optimal level of training provided by the government of S.

Introducing discounting into the objective function of the host country is much more complex, as it requires strong assumptions on the time path of public-service consumption of the immigrant household. However, if the time path of service consumption grows at the same rate as the benefits enjoyed by the host country due to growth in the migrant's productivity, discounting does not affect our results concerning the host country.



## 4.10 Appendix D: Endogenous skill formation

### 4.10.1 D.1: Autarky case

Consider an individual whose lifetime consists of two phases. In the first phase she has to decide on how to optimally divide her endowment of one unit of time between leisure,  $l$ , and studies,  $z$ . The skills acquired in the first phase determine her income and consumption in the second phase. Utility is derived from leisure,  $l$ , in the first phase and consumption of commodities,  $C$ , in the second phase according to  $U(l, C) = u^*(l) + u(C)$ . We adopt the standard assumptions:  $u^*(l) > 0$ ,  $u^{*''}(l) < 0$ ,  $u'(C) > 0$ , and  $u''(C) < 0$ . By investing more of her time into education, the individual can increase her productivity and hence total consumption,  $C$ , in the second phase. More precisely,  $C(z, \varepsilon) = TH^*(z, \varepsilon)$  with  $H_z^* > 0$ ,  $H_\varepsilon^* > 0$ ,  $H_{zz}^* < 0$ ,  $H_{\varepsilon\varepsilon}^* < 0$ , and  $H_{z\varepsilon}^* > 0$ , where  $T$  is the length of the second phase and  $\varepsilon$  is the level of public education provided by the authorities.

The optimization problem of the individual is

$$\max_z u^*(1 - z) + u(C(z, \varepsilon)),$$

taking  $\varepsilon$  as given. The first-order condition reads:

$$-u^{*'}(1 - z) + u'(C) \frac{\partial C}{\partial z} = 0.$$

By totally differentiating the above expression we obtain:

$$\frac{dz}{d\varepsilon} = - \frac{u''(C) \frac{\partial C}{\partial z} \frac{\partial C}{\partial \varepsilon} + u'(C) \frac{\partial^2 C}{\partial z \partial \varepsilon}}{u^{*''}(1 - z) + u''(C) \left( \frac{\partial C}{\partial z} \right)^2 + u'(C) \frac{\partial^2 C}{\partial z^2}},$$

where the denominator is unambiguously negative, while the two terms in the numerator have conflicting signs: both  $\frac{\partial C}{\partial z} \frac{\partial C}{\partial \varepsilon}$  and  $\frac{\partial^2 C}{\partial z \partial \varepsilon}$  are positive, while  $u''(C) < 0$  and  $u'(C) > 0$ . If we consider, however, the usual iso-elastic utility functions:

$$u^*(l) = \frac{l^{1-\chi}}{1-\chi}, \quad \chi \in (0, 1), \quad u(C) = \frac{C^{1-\sigma}}{1-\sigma}, \quad \sigma \in (0, 1),$$

and assume that  $H^*(z, \varepsilon) = \mu^* \varepsilon^\beta z^\kappa$ , with  $\mu^* > 0$  being a technological parameter,  $\beta \in (0, 1)$ ,  $\kappa \in (0, 1)$ , and  $\beta + \kappa < 1$ , then we can write

$$\frac{dz}{d\varepsilon} = \frac{(T\mu^*)^{1-\sigma} \kappa \beta (1-\sigma) \varepsilon^{\beta(1-\sigma)-1} z^{\kappa(1-\sigma)-1}}{\chi(1-z)^{-(\chi+1)} - (T\mu^*)^{1-\sigma} \kappa (\kappa - 1 - \sigma \kappa) \varepsilon^{\beta(1-\sigma)} z^{\kappa(1-\sigma)-2}} > 0,$$

indicating that if the authorities choose to provide a higher  $\varepsilon$ , this triggers more effort on the part of students.

In sum, with endogenous skill formation, the marginal productivity of an agent in equilibrium depends on  $\varepsilon$  through two channels: one direct, as described in the main text, and an indirect channel through the study effort optimally chosen by the individual,  $z(\varepsilon)$ . We thus have  $H^*(\varepsilon, z(\varepsilon))$ , with  $dH^*/d\varepsilon = \partial H^*/\partial \varepsilon + (\partial H^*/\partial z) \partial z/\partial \varepsilon$ , where the first term is the direct positive effect of  $\varepsilon$  and the second term corresponds to the indirect "effort" effect.

#### 4.10.2 D.2: Temporary Migration

When the option to migrate temporarily becomes available, the expected lifetime income and consumption of a representative source-country worker becomes

$$C = p[\tau(1-\theta)w + (T-\tau)\phi H(\varepsilon, z, \tau)] + (1-p)TH^*(\varepsilon, z),$$

where  $p \equiv M/(\tau L^*)$  represents the probability to migrate and  $H(\varepsilon, z, \tau)$  is the migrant's productivity while abroad, a fraction  $\phi$  of which is transferable to S at the point of return and compensated in the form of correspondingly higher earnings. The term in the square brackets is thus the lifetime income of a migrant, i.e., the sum of the (after-tax) income earned abroad for  $\tau$  units of time and the income earned after return for  $T - \tau$  units of time. The last term is simply the product of  $1 - p$  and the lifetime income of a non-migrant. We have already assumed in the main text that  $H_\tau > 0$ ,  $H_{\tau\tau} < 0$ ,  $H_\varepsilon > 0$ ,  $H_{\varepsilon\varepsilon} < 0$ ,  $H_{\varepsilon\tau} \geq 0$ , and now we add the assumptions that  $H_z > 0$ ,  $H_{zz} < 0$ ,  $H_{z\varepsilon} > 0$  and finally  $H_{z\tau} > 0$ .

The optimality condition for the choice of study effort,  $z$ , becomes:

$$u^*(1-z) = u'(C) [p(T-\tau)\phi H_z + (1-p)TH_z^*]. \quad (4.35)$$

Note that an increase in study effort helps increase a migrant's earnings *only after* return, given that the foreign wage  $w$  is fixed, while it raises the earnings of a non-migrant over the entire period  $[0, T]$ . Moreover,  $z$  does not affect the probability of migration, as all individuals are identical and the stock of migrants abroad is fixed by the immigration policy of the host country.

By differentiating the above expression we obtain

$$\frac{dz}{d\tau} = -\frac{u''(C)\frac{\partial C}{\partial z}\frac{\partial C}{\partial \tau} + u'(C)\frac{\partial^2 C}{\partial z\partial \tau}}{u^{*''}(1-z) + u''(C)\left(\frac{\partial C}{\partial z}\right)^2 + u'(C)\frac{\partial^2 C}{\partial z^2}}. \quad (4.36)$$

Since  $\frac{\partial^2 C}{\partial z^2} < 0$ , the sign of the denominator is clearly negative. Accordingly, the sign of  $\frac{dz}{d\tau}$  is the same as the sign of the numerator, which involves the following terms:

$$\frac{\partial C}{\partial z} = p(T - \tau)\phi H_z + (1 - p)TH_z^* > 0, \quad (4.37)$$

$$\frac{\partial C}{\partial \tau} = \frac{p}{\tau} [T(H^* - \phi H) + (T - \tau)\phi \eta_{H\tau} H] \geq 0, \quad (4.38)$$

$$\frac{\partial^2 C}{\partial z\partial \tau} = \frac{p}{\tau} [TH_z^* - (T - \tau)\phi H_z] - p\phi [H_z - (T - \tau)H_{z\tau}] \geq 0. \quad (4.39)$$

Eq. (4.37) shows that an increase in the study effort enhances the earnings of an individual by increasing her productivity after return, if she migrates, and over the entire second phase ( $T$ ), if she stays permanently at home. Expressions (4.38) and (4.39) are more complex. An increase in  $\tau$  reduces the probability of migration, as well as the amount of time that a returnee works in S, earning  $\phi H(\varepsilon, z, \tau)$  instead of the foreign, presumably higher, wage  $w$ . After some simplifications, it can be shown that this effect operates in the direction of making  $\frac{\partial C}{\partial \tau}$  negative if, as might be expected, the productivity of a returnee,  $\phi H(\varepsilon, z, \tau)$ , is greater than that of a non-migrant,  $H^*(\varepsilon)$ . This effect is captured by the first term of the bracketed expression in (4.38). A longer duration of stay abroad also makes a returnee more productive at home. This effect contributes to  $\frac{\partial C}{\partial \tau}$  being positive and it corresponds to the second term

in the brackets, where  $\eta_{H\tau} \equiv \frac{\partial H}{\partial \tau} \frac{\tau}{H} > 0$ . In consequence, the sign of  $\frac{\partial C}{\partial \tau}$  is ambiguous.

Let us consider next  $\frac{\partial^2 C}{\partial z \partial \tau}$  in (4.39). Because an increase in  $\tau$  tends to lower the probability of migration, it lowers (raises)  $\frac{\partial C}{\partial z}$  if additional study effort raises (respectively, lowers) the earnings of a returnee over  $T - \tau$  units of time by more than it does the productivity of a non-migrant over the entire second phase,  $T$ . This effect is captured by the first term in (4.39). An increase in  $\tau$  also reduces the duration of a returnee's stay at home, but increases her earnings over that period of time as more skills are acquired abroad. These two conflicting effects on  $\frac{\partial^2 C}{\partial z \partial \tau}$  are captured by the two expressions in the second bracketed term of (4.39).

In summary, the signs of both (4.38) and (4.39) can be either positive or negative for realistic values of the model's parameters. Accordingly, without knowing all the relevant parameter values, it is not possible to determine the sign of  $\frac{dz}{d\tau}$  and hence the impact of a change in  $\tau$  on the optimal amount of study effort of each citizen of S. For this reason, we have chosen not to endogenize study effort in the main body of the paper but merely explore the possible consequences of doing so in this Appendix.

## Figures

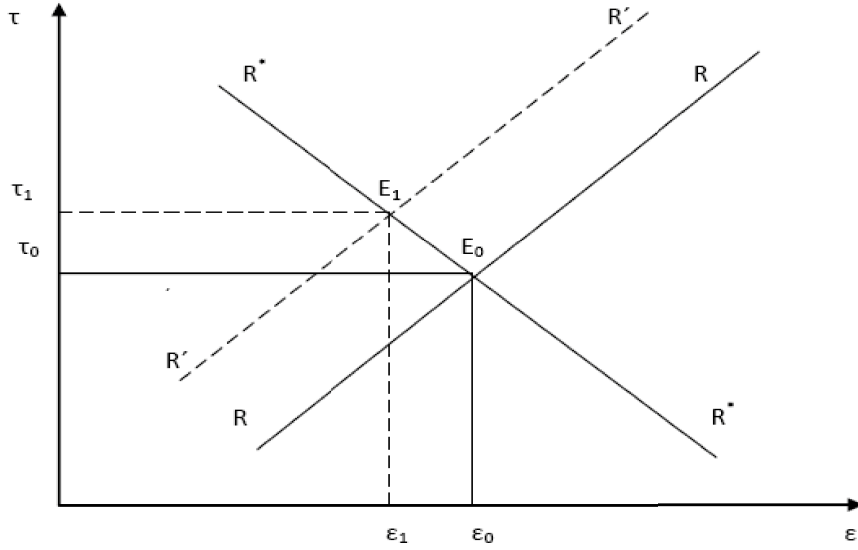


Figure 4.1: Nash equilibrium when  $R^*R^*$  is negatively sloped ( $W_{\epsilon\tau}^* < 0$ ).

Solid lines depict the Nash equilibrium when the source country's reaction function  $R^*R^*$  is negatively sloped ( $W_{\epsilon\tau}^* < 0$ ). A higher tax rate on earnings in the host country, a lower cost of public services provided to immigrants or a higher weight attached to employers' rents in F, result in an upward shift of the host country's reaction function to  $R'R'$ , and hence a longer duration of the work permit and a lower level of public training.

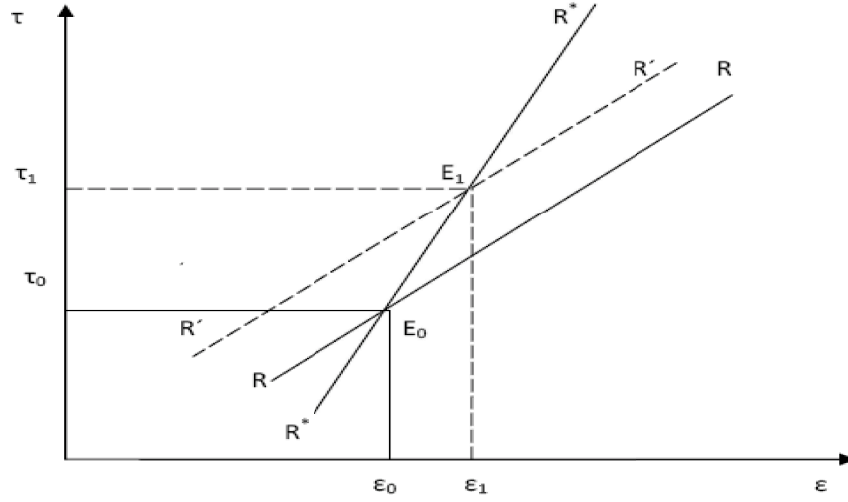


Figure 4.2: Nash equilibrium when  $R^*R^*$  is positively sloped ( $W_{\varepsilon\tau}^* > 0$ ).

Solid lines depict the Nash equilibrium when the source country's reaction function  $R^*R^*$  is positively sloped ( $W_{\varepsilon\tau}^* > 0$ ). A higher tax rate on earnings in F, a lower cost of hosting immigrants or a higher weight attached to employers' rents in F result in a longer duration of the work permit and more expenditure on public training provided by country S.

## Part II

# Uncertain Backstop and Environmental Agreements

## Chapter 5

# Investment in an Uncertain Backstop: Optimal Strategy for an Open Economy

### 5.1 Introduction

Interest in private and public investment projects devoted to research and development of renewable energy sources ("backstops") is primarily based on concerns about exhaustion of non-renewable energy resources and their ever increasing market price. If we look across countries at the leading investors in energy R&D in per capita terms, we find Japan occupying the first place (IEA 2006). Not surprisingly, this country is also well known for its heavy dependence on energy imports.<sup>1</sup> Within the European Union, the economies leading the way in terms of their share of national income devoted to renewable energy sources are Denmark, Finland, the Netherlands, and Sweden (European Commission 2004). These are again countries that do not possess large stocks of fossil fuels, making them heavily dependent on imports (except

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<sup>1</sup>Although Japan is only the second largest oil importer after the United States, it meets a larger share of its energy needs through imports of oil than the U.S. does (U.S. Energy Information Administration, <http://www.eia.doe.gov/country/index.cfm>).



for the Netherlands which do possess large reserves of natural gas).

The purpose of the present paper is to study the problem facing a resource-importing country, hereafter RIC, which seeks to achieve energy independence by developing a substitute for the non-renewable importable input. This is assumed to require sustained investment in an R&D program. Arrival of the substitute follows a stochastic process with the probability of a successful outcome per unit of time being a non-decreasing function of the rate of investment in R&D. Apart from trade in the resource market, RIC can also participate in the global financial market. This latter dimension is most often overlooked in the literature on backstop technology and resource management in general. As we shall see, however, access to international lending and borrowing is important in several dimensions, especially if a country is heavily dependent on imports of an essential input.

The literature on backstop-technology adoption has its origins in the wake of the oil price shock of 1973. The early contributions focus on a closed economy, endowed with a known stock of an exhaustible resource, seeking to sustain its consumption in the long run by appropriately substituting a renewable backstop for the non-renewable essential input. The arrival date of the substitute is assumed to be either known with certainty or uncertain but governed by an exogenous stochastic process (see, e.g., Dasgupta and Heal 1974, Dasgupta and Stiglitz 1981). The seminal contribution of Kamien and Schwartz (1978) extends this analysis by endogenizing the uncertain arrival date through investment in R&D. Hung and Quyen (1993) go further to determine the optimal time to initiate the R&D project, although their R&D investment policy is simplified to a single-date expenditure, after which a backstop may arrive with a constant Poisson rate. Tsur and Zemel (2003) propose an alternative (deterministic) framework of analysis, where the cost of the backstop falls continuously as the knowledge base accumulates through R&D. This ensures a continuous transition from the non-renewable to the backstop. Their model advocates an R&D policy characterized by the most rapid approach path to the target-knowledge process which should then be

followed forever. The work of Dasgupta, Gilbert and Stiglitz (1983) shows, also in the context of a deterministic model, that the intention to develop a substitute and its eventual arrival can trigger a strategic response from resource owners. Harris and Vickers (1995) study a similar dynamic game, except that the substitute's arrival is random and exponentially distributed.

Although the two latter contributions are concerned with open economies, their analysis is limited to exchange of the resource for the consumption good, while the possibility of international lending and borrowing is ruled out. The trade-theoretic literature, on the other hand, deals with problems related to exhaustible resource management and, in some cases, for countries that have access to foreign credit, but it does not address the problem of optimal investment in the development of a backstop technology.<sup>2</sup> Moreover, these contributions consider purely deterministic models and therefore exclude the possibility of uncertainty affecting behavior.<sup>3</sup> The purpose of the present study is to bridge the existing gap between the closed-economy analysis of investment in a backstop technology and open-economy models of trade in goods and financial assets within a fully dynamic stochastic optimization framework. This will make it possible for us to examine the role of international financial markets in influencing optimal investment strategies in a stochastic environment, an issue of increasing importance in a world where energy prices and international indebtedness are becoming dominant themes.

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<sup>2</sup>Kemp and Long (1984) do consider resource replacement but in a deterministic setting, where the resource price is exogenous and constant and there is no possibility to participate in the international financial markets. Djajić (1988) considers a two-country world, where both countries are endowed with some stock of the resource and can lend or borrow from each other at an endogenously determined rate of interest. The dynamics of his model are, however, limited to only two time periods and neither country intends to develop a backstop.

<sup>3</sup>An exception is Dasgupta, Eastwood and Heal (1978) who do consider uncertainty related to future energy demand. They also introduce a possibility to accumulate a foreign asset yielding a constant rate of return but focus on a resource-exporting economy, which is not engaged in any R&D activity.

In order to highlight the role of access to credit, I first present in Section 2 a model of a resource-importing economy which may choose to engage in development of an energy substitute under financial autarky. Section 3 extends the model to allow for international lending and borrowing. Section 4 solves the two models numerically and analyzes the optimal R&D investment rate, the time profile of consumption and the net foreign asset position before and after the invention of a substitute (if such happens to occur). Access to international lending and borrowing allows for a more efficient intertemporal allocation of resources and a higher lifetime welfare as compared with the case of financial autarky. While this is generally to be expected, a comparison of the optimal investment rates under financial autarky and access to foreign credit enables us to address a number of entirely new issues. First, there is the question of how the degree of dependency on imported energy resources affects the economy's optimal investment in the development of a backstop. On the one hand, greater dependency makes it more urgent to discover a substitute. On the other hand, it also implies a larger import bill prior to invention, which tightens the economy's budget constraint and makes any given investment program relatively more burdensome. My analysis shows that for empirically plausible values of the elasticity of intertemporal consumption substitution, greater dependency on resource imports entails a lower investment rate, with access to foreign credit having a moderating influence. The second set of issues concerns the role of the cost of credit which influences not only the time path of the country's net foreign asset position but the optimal investment decision as well. The paper concludes in Section 5 with a summary of the main results.

## 5.2 Financial Autarky

Let me introduce the assumptions and the notation by starting with the simplest case of financial autarky. Consider a resource-importing country (RIC)

which produces a composite consumption good according to the production function

$$Y_t = F(R_t, L), \quad (5.1)$$

where  $F(., .)$  is a strictly increasing, concave and twice-differentiable function of both arguments,  $L$  is the constant labor input and  $R_t$  is the resource input, which must be entirely imported from abroad. The price of the resource, measured in terms of the consumption good, satisfies  $P_t = P_0 e^{rt}$ ,  $P_0$  known, and  $r$  is a constant growth rate. RIC wishes to develop a backstop, i.e., to invent and produce a substitute for the resource, but this requires setting up and maintaining an R&D lab.<sup>4</sup> RIC may invest  $m_t \geq 0$  units of the consumption good each period to keep the lab operational. The discovery of a substitute follows a stochastic process which can be influenced by the investment decision. Let  $(\Omega, \mathcal{F}, \mathcal{P})$  be a probability space, and let  $\tau$  be a random variable, which I call the arrival date of the substitute. I assume that the probability measure  $\mathcal{P}$  depends on the investment rate in the following way

$$\mathcal{P}[\tau \in (t, t + dt) | \tau \geq t] = q(m_t)dt + o(dt),$$

where  $q : \mathbb{R}^+ \rightarrow \mathbb{R}^+$  and its first derivative  $q'(m_t)$  are continuous functions,  $q(0) \geq 0$  and the limit of  $o(dt)/dt$  is zero as  $dt \rightarrow 0$ .

If the backstop arrives, a known quantity  $B$  of the substitute becomes available every period at zero cost.<sup>5</sup> This quantity simply substitutes for the resource input in the production function. The flow of output is then constant

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<sup>4</sup>The model assumes that once the substitute is invented, RIC becomes its unique owner. This occurs, for instance, if the substitute (or its production process) is specific to RIC's geographic location or if RIC can patent the invention. I do not, however, analyze issues related to patent races.

<sup>5</sup>Allowing for a cost of production which is positive, constant or varying over time but exogenous, will merely affect the relevant budget constraint in a straightforward manner. The qualitative results will remain intact.

and given by  $\bar{Y} = F(B, L)$  and the resource is no longer imported.<sup>6</sup>

The social planner's objective is to maximize the expected lifetime welfare by choosing the optimal consumption rate,  $c_t$ , the investment rate,  $m_t$ , and imports of the resource,  $R_t$ , given the constant rate of time preference,  $\rho$ , and the resource price path:

$$\max_{c_t, m_t, R_t} \int_0^\infty \left\{ \int_0^\tau u(c_t) e^{-\rho t} dt + \int_\tau^\infty u(\tilde{c}) e^{-\rho t} dt \right\} f_\tau d\tau, \quad (5.2)$$

subject to the constraints

$$c_t = F(R_t, L) - P_t R_t - m_t, \quad (5.3)$$

$$\tilde{c} = \bar{Y},$$

$$f_\tau = q(m_\tau) e^{-\int_0^\tau q(m_s) ds},$$

where  $u(\cdot)$  is a strictly increasing, concave and twice-differentiable function with  $\lim_{c \rightarrow 0} u'(c) = \infty$ . The consumption rate in Phase II, i.e., after the discovery has taken place, is denoted by  $\tilde{c}$ . Note that once the substitute has arrived, there is no more need to maintain the R&D investment.

This stochastic control problem can be analyzed with the aid of the Hamiltonian (see Boukas et al. (1990) or the Appendix):

$$H = \left\{ u(F(R_t, L) - P_t R_t - m_t) + q(m_t) \frac{u(\bar{Y})}{\rho} \right\} e^{-\rho t - z_t} + \nu_t q(m_t), \quad (5.4)$$

where  $z_t$  is an auxiliary state variable such that  $\dot{z}_t \equiv \frac{dz_t}{dt} = q(m_t)$ ,  $z_0 = 0$ , and  $\nu_t$  is the associated co-state variable. The necessary conditions for optimality

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<sup>6</sup>If  $B$  is not large enough, however, it may be optimal to continue importing energy from abroad until its price rises sufficiently to reduce the demand to the available per-period supply of the substitute. In the present paper I do not analyze the optimal timing of the switch from the non-renewables to the backstop (which can be the topic of a separate paper) and wish to focus only on the optimal investment strategy under uncertainty. In the rest of the analysis I therefore assume that  $B$  is sufficiently large, i.e.,  $B \geq g(P_0 e^{r\tau})$ ,  $\forall \tau$ , where function  $g(\cdot)$  is the inverse of the marginal productivity of the resource. In particular, it is sufficient to assume that  $\partial F(B, L)/\partial B \leq P_0$ , so that it is no longer optimal to continue importing the exhaustible resource even if the substitute becomes available from the start. See Amigues et al. (1998) for treatment of a capacity constraint on the flow of the substitute.

consist of

$$R_t : \quad u'(c_t) \left( \frac{\partial F_t}{\partial R_t} - P_t \right) e^{-\rho t - z_t} = 0, \quad (5.5)$$

$$m_t : \quad \left\{ -u'(c_t) + q'(m_t) \frac{u(\bar{Y})}{\rho} \right\} e^{-\rho t - z_t} + \nu_t q'(m_t) = 0, \quad (5.6)$$

$$z_t : \quad \left\{ u(c_t) + q(m_t) \frac{u(\bar{Y})}{\rho} \right\} e^{-\rho t - z_t} = \dot{\nu}_t \quad (5.7)$$

and the budget constraint (5.3). Eq. (5.5) is the efficiency in production condition, which requires that the marginal productivity of the resource input equals its price. Eq. (5.6) guarantees the optimality of investment by equating the present value of the marginal investment cost,  $u'(c_t)e^{-\rho t - z_t}$ , to the present value of the marginal expected benefit,  $q'(m_t) \left[ \frac{u(\bar{Y})}{\rho} e^{-\rho t - z_t} + \nu_t \right]$ . Eq. (5.7) describes the dynamics of the co-state variable.

Given the structure of the production technology (5.1), eq. (5.5) relates the quantity of imports to the resource price as  $R_t = g(P_t)$ , where  $g(\cdot)$  is the inverse function of the marginal productivity of resource with  $g'(\cdot) < 0$ . Define the net output as  $Y_t^n \equiv F(R_t, L) - P_t R_t$ . Then the value of  $Y_t^n$  at each point in time is determined by  $P_t$ :

$$Y_t^n = F(g(P_t), L) - g(P_t)P_t \quad (5.8)$$

with  $\frac{\partial Y_t^n}{\partial P_t} = -g(P_t) < 0$ ,  $\frac{\partial^2 Y_t^n}{\partial P_t^2} = -g'(P_t) > 0$ . The budget constraint (5.3) may then be rewritten as

$$c_t = Y_t^n(P_t) - m_t. \quad (5.9)$$

Solving for  $\nu_t$  from (5.6), differentiating with respect to time and inserting the result in (5.7) yields

$$\dot{m}_t = \frac{q'(m_t)}{q''(m_t)} \left[ \frac{q'(m_t)[u(\bar{Y}) - u(c_t)]}{u'(c_t)} + \frac{u''(c_t)\dot{c}_t}{u'(c_t)} - \rho - q(m_t) \right],$$

which, in combination with (5.8) and (5.9), can be solved for the optimal time path of investment.

From this point on, let me assume for simplicity that the investment rate is time-invariant, i.e.,  $m_t = m$ ,  $\forall t$ , which means that RIC must commit itself to a certain constant expenditure per unit of time to keep the R&D lab operational.<sup>7</sup> Then the optimal investment rate under financial autarky,  $m^{*FA}$ , solves

$$-\frac{u''(c_t)c_t}{u'(c_t)}\hat{c}_t = q'(m) \left[ \frac{u(\bar{Y}) - u(c_t)}{u'(c_t)} \right] - \rho - q(m), \quad (5.10)$$

where the first term on the right-hand side corresponds to the economy's implicit rate of interest.

Total differentiation of eq. (5.10) yields

$$\Delta_m dm = \Delta_P dP_0 + \Delta_r dr + \Delta_B dB + \Delta_\rho d\rho,$$

where

$$\begin{aligned} \Delta_m &\equiv g(P_t)\dot{P}_t \left[ \frac{u'''(c)u'(c) - (u''(c))^2}{(u'(c))^2} \right] - \frac{u(\bar{Y}) - u(c)}{u'(c)} \left[ q''(m) + \frac{q'(m)u''(c)}{u'(c)} \right], \\ \Delta_P &\equiv \Omega \frac{dP_t}{dP_0}, \quad \text{where} \quad \frac{dP_t}{dP_0} = e^{rt} > 0, \quad \Omega = -r^2 e^{rt} \frac{u''(c)}{u'(c)} [g'(P_t)P_t + g(P_t)] + \\ &+ \left\{ q'(m) \frac{[(u'(c))^2 + (u(\bar{Y}) - u(c))u''(c)]}{(u'(c))^2} - g(P_t)\dot{P}_t \left[ \frac{u'''(c)u'(c) - (u''(c))^2}{(u'(c))^2} \right] \right\} g(P_t), \\ \Delta_r &\equiv \Omega \frac{dP_t}{dr}, \quad \text{where} \quad \frac{dP_t}{dr} = tP_t \geq 0 \\ \Delta_B &\equiv q'(m) \frac{u'(\bar{Y}) \frac{\partial \bar{Y}}{\partial B}}{u'(c)} > 0, \\ \Delta_\rho &= -1, \end{aligned}$$

The term  $\Delta_m$  is, in general, of ambiguous sign. However, for standard utility functions employed in the literature, such as CRRA and negative exponential,

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<sup>7</sup>Hung and Quyen (1993) also use a fixed investment assumption, although in their setting R&D investment is modeled as a single expenditure at the initial point in time which determines the arrival rate of a substitute. By contrast, in the present analysis,  $m$  must be invested at each point in time, so that the sacrifice of current consumption becomes more and more difficult to support as the time goes by without the substitute being invented.

the term  $u'''(c)u'(c) - (u''(c))^2$  is non-negative,<sup>8</sup> while for a concave  $q(m)$  function the term  $q''(m)$  is negative. This is sufficient to ensure that  $\Delta_m > 0$ . The terms  $\Delta_P$  and  $\Delta_r$  are of ambiguous sign since  $\Omega \geq 0$  and therefore the effects of  $P_0$  and  $r$  on the optimal investment rate, i.e.,  $\frac{dm}{dP_0} = \frac{\Delta_P}{\Delta_m}$  and  $\frac{dm}{dr} = \frac{\Delta_r}{\Delta_m}$  are ambiguous. This is hardly surprising. An increase in the resource price generates two conflicting effects: On the one hand, it tightens the economy's budget constraint as the import bill expands. On the other hand, it makes the development of the backstop more urgent as the economy's dependency on energy resources, whose market price rises exponentially, is increased. If the social planner of this economy is risk-neutral, we obtain

$$\frac{dm}{dP_0} = -\frac{q'(m)g(P_t)e^{rt}}{q''(m)\frac{u(\bar{Y})-u(c)}{u'(c)}} > 0, \quad \frac{dm}{dr} = -\frac{q'(m)g(P_t)tP_t}{q''(m)\frac{u(\bar{Y})-u(c)}{u'(c)}} \geq 0,$$

where the numerators are unambiguously non-negative and the denominators are negative if  $q(m)$  is concave or  $m$  lies in the concave region of  $q(\cdot)$ . A risk-neutral planner will therefore react to an increase in the resource price or its growth rate by increasing investment in R&D. The effect of a change in the rate of time preference is given by  $\frac{dm}{d\rho} = \frac{\Delta_\rho}{\Delta_m} < 0$ , so that patient economies will tend to choose a higher investment rate. An increase in the flow of the backstop unambiguously calls for an increase in the R&D investment rate:  $\frac{dm}{dB} = \frac{\Delta_B}{\Delta_m} > 0$ . We will be able to gain more insight about how the optimal investment rate responds to variations in  $B$ ,  $P_0$ ,  $\rho$ ,  $r$ , and other variables, such as the elasticity of intertemporal consumption substitution, in Section 4, where the model is solved numerically.

Transactions with the rest of the world are limited so far to the exchange of the consumption good for the resource. I examine next how the optimal investment strategy is affected if RIC has the possibility to lend and borrow in the international financial markets. It is clear that access to a riskless saving technology allows to implement a smoother optimal consumption path.

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<sup>8</sup>This term is equal to zero for the class of negative exponential functions of the type  $u(c) = -e^{-\theta c}$  and for linear utility functions. It is strictly positive for negative exponential utility of the type  $u(c) = -e^{1/c}$  and for widely used in the literature CRRA utility.



However, the following questions remain: To what extent does access to foreign credit alleviate the burden of investment, facilitating development of a more ambitious project? What role does foreign credit play when RIC's dependency on energy imports is increased? What is the role of the cost of credit? What is the optimal time profile of the net foreign asset position and how is it affected by the arrival of the backstop? Sections 3 and 4 address these and other related questions.

### 5.3 Access to World Financial Markets

In this section I allow RIC to have access to international financial markets, where a single riskless asset, denominated in units of the consumption good, is costlessly traded. The asset yields a constant world rate of return,  $r$ .<sup>9</sup> By arbitrage, the growth rate of the resource price must also be equal to  $r$ , assuming that extraction is costless (Hotelling, 1931).

Let  $a_t$  denote RIC's net foreign asset position at time  $t$ . Assuming that the time horizon is infinite, the budget constraints in the first and the second phases respectively are

$$\dot{a}_t = F(B, L) - P_t R_t - m + r a_t, \quad \forall t \in [0, \tau), \quad a_0 \text{ given}, \quad (5.11)$$

$$\dot{a}_t = F(B, L) - \tilde{c}_t + r a_t, \quad \forall t \geq \tau, \quad (5.12)$$

$$\lim_{t \rightarrow \infty} a_t e^{-rt} = 0. \quad (5.13)$$

Eq. (5.11) states that during the first phase, while the substitute is not yet available, the rate of accumulation of foreign assets is equal to the total output minus expenditure on consumption, resource imports and investment, plus interest earned (paid) on the accumulated assets (outstanding debts). Eq. (5.12) states that during the second phase, the change in the asset position

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<sup>9</sup>Treating  $r$  as exogenous is based on the assumption that RIC's borrowing to finance (in part) its R&D efforts does not have a perceptible impact on the world rate of interest. Given the size of the global financial markets in relation to that of a major investment project in any one country, this assumption is arguably the most appropriate.

is just equal to the constant flow of output minus consumption plus interest, and the resource is no longer imported. RIC's objective is to maximize (5.2) subject to (5.11) - (5.13).

The solution method consists of two steps. First, the maximized value of discounted (time- $\tau$ ) welfare in Phase II is obtained, given the net foreign asset position at  $t = \tau$ . I call this function  $\Phi(a_\tau)$ . Then, the total lifetime welfare is maximized, given the relationship between  $a_\tau$  and the welfare in Phase II (detailed derivation is relegated to the Appendix).

Consider the optimization problem pertaining to Phase II. RIC seeks to maximize

$$\int_{\tau}^{\infty} u(\tilde{c}_t) e^{-\rho(t-\tau)} dt \quad (5.14)$$

subject to (5.12) - (5.13) and  $a_\tau$  given. The solution for the optimal  $\tilde{c}_t$  is obtained in a straightforward manner using the standard dynamic optimization technique:

$$\tilde{c}_t = \tilde{c}_\tau e^{\frac{r-\rho}{\theta}(t-\tau)}, \quad \forall t \geq \tau, \quad \tilde{c}_\tau = \left( r - \frac{r-\rho}{\theta} \right) \left( a_\tau + \frac{\bar{Y}}{r} \right). \quad (5.15)$$

Then, the maximized value of (5.14), is

$$\Phi(a_\tau) = u(\tilde{c}_\tau) \left( r - \frac{r-\rho}{\theta} \right)^{-1}.$$

The Hamiltonian, associated with RIC's original optimization problem may then be written as

$$H = \left\{ u(c_t) + q(m) \Phi(a_t) \right\} e^{-\rho t - z_t} + \eta_t [ra_t + F(R_t, L) - c_t - P_t R_t - m] + \nu_t q(m),$$

where  $\eta_t$  is the co-state variable associated with the constraint (5.11) and  $z_t$  is the auxiliary state variable, as in Section 2. The solution is implicitly given by the system:

$$-\frac{u''(c_t)c_t}{u'(c_t)}\hat{c}_t = r - \rho - q(m) \left[ 1 - \frac{u'(\tilde{c}_t)}{u'(c_t)} \right] \quad (5.16)$$

$$\tilde{c}_t = \left( r - \frac{r-\rho}{\theta} \right) \left( a_t + \frac{\bar{Y}}{r} \right), \quad (5.17)$$

$$q'(m) [\rho \Phi(a_t) - u(c_t) - u'(\tilde{c}_t)\dot{a}_t] = u'(c_t)r + q(m)u'(\tilde{c}_t), \quad (5.18)$$

$$\dot{a}_t = F(R_t, L) - c_t - P_t R_t - m + ra_t, \quad a_0 \text{ given.} \quad (5.19)$$

Eq. (5.16) describes the growth rate of consumption in Phase I. Note that if there is no uncertainty, the last term vanishes and the standard Keynes-Ramsey rule applies. When  $q(m) > 0$ , the standard rule is modified to account for the effect of uncertainty. The term in the square brackets is unambiguously positive since  $\tilde{c}_t > c_t$  and therefore consumption grows at a lower rate, as compared to the certainty case. The lower optimal growth rate (or a more rapid decline) of consumption results in a higher dissaving rate at the beginning of the planning horizon in anticipation of the possible technological break-through. Moreover, the higher the flow of the substitute,  $B$ , in the event of a discovery, the lower the consumption growth rate and the higher the dissaving rate at the beginning of the planning horizon.

Eq. (5.17) determines the time- $\tau$  consumption rate, i.e., the consumption rate to which the economy jumps at the moment when the backstop arrives. It depends negatively (positively) on the stock of debt (assets) accumulated up to the time of the invention.<sup>10</sup> From time  $\tau$  onwards the consumption rate during Phase II is no longer constant, as it was under financial autarky, but grows or contracts depending on the difference between the world rate of interest and RIC's rate of time preference, satisfying the standard Keynes-Ramsey rule. Without access to credit, Phases I and II were disconnected, in the sense that the optimal consumption rate in Phase II was independent of the variables pertaining to Phase I.<sup>11</sup> In the present setting, the two phases are connected through the net foreign asset position held at the time of invention. Eq. (5.18) is the optimality condition for the choice of  $m$ , which states that the marginal expected benefit from undertaking the investment must be equal to the marginal cost, which also includes the opportunity cost of not investing in the capital markets. The system (5.16) - (5.19) is solved numerically and

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<sup>10</sup>Convergence of the integral in (5.14) requires that  $\frac{r-\rho}{\theta} - r < 0$ , so that  $\partial \tilde{c}_\tau / \partial a_t = r - \frac{r-\rho}{\theta} > 0$ .

<sup>11</sup>This is the reason why Kamien and Schwartz (1978) are able to summarize the value function pertaining to Phase II by the variable  $W$  which is taken to be exogenous and, more importantly, independent of the arrival date of the backstop.

analyzed in the next section.

## 5.4 Numerical Illustration and Discussion

This Section compares the solution to RIC's problem with access to credit (AC, for short) with the one under financial autarky (FA, for short). The objective is to analyze how the economy's dependence on energy resources translates into the choice of  $m$  and what role access to international capital markets plays in this respect. I also examine the optimal borrowing/lending strategy in an uncertain environment.

Let the utility function take the usual iso-elastic form  $u(c) = \frac{c^{1-\theta}}{1-\theta}$ , where  $\theta \equiv -\frac{u''(c_t)c_t}{u'(c_t)}$  is the inverse of the elasticity of intertemporal consumption substitution. The production function is of the Cobb-Douglas type:  $Y_t = AR_t^\alpha L^{1-\alpha}$ ,  $0 < \alpha < 1$ ,  $A > 0$ . I assume that the invention of the substitute follows a Poisson process with the arrival rate  $\lambda(m)$ .<sup>12</sup> The arrival rate is positively related to the R&D investment rate, i.e.  $\lambda'(m) > 0$ . It is assumed that  $\lambda''(m) > 0$  for  $m < \bar{m}$  and  $\lambda''(m) < 0$  for  $m > \bar{m}$ . That is, when the investment rate is relatively small, commitment to an additional unit of sustained investment has an increasing marginal impact on the probability of making a discovery. Alternatively, when the investment rate is already high, the impact of an extra unit on the arrival rate is diminishing.<sup>13</sup> A natural

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<sup>12</sup>As emphasized by Wälde (1999), Poisson processes describe quite well various economic activities involving zero-one outcomes per unit of time as, for example, job search or search for a new technology. In his decentralized model, the Poisson arrival rate is an increasing function of aggregate R&D investment but his analysis is limited to the linear class of functions.

<sup>13</sup>In the model of Kamien and Schwartz (1978) it is assumed that the probability of discovering a substitute depends on the *cumulative* R&D effort. The rate of growth of R&D effort is, in turn, a concave function of investment. In their suggestions for possible extensions K&S write that "successful development of a new technology may require a sustained commitment of resources above a minimal level." Here I follow this route in

candidate for the  $\lambda$ -function is a sigmoid-type function since it possesses the property that I have just outlined: convexity up to a certain (inflection) point and concavity thereafter. I specify the exact functional form for  $\lambda(m)$  to be

$$\lambda(m) = (T_{min} + e^{(\mu - \gamma m)/\sigma})^{-1}, \quad (5.20)$$

where  $T_{min} \geq 0$  is the shortest possible time needed for the development of a backstop, and  $\mu$ ,  $\gamma$ , and  $\sigma$  are positive parameters calibrated as  $\mu = \ln(T - T_{min})$ ,  $\gamma = 15$ ,  $\sigma = 1$ . A higher (lower)  $\gamma$  makes the slope steeper (flatter). The chosen values of  $\mu$  and  $\sigma$  ensure that  $\lambda(0) = 1/T$ , where  $T$  is the length of the economy's planning horizon. This latter condition states that if the economy chooses a zero investment rate, there is still a chance of discovering a backstop once in  $T$  units of time. The inflection point  $\bar{m} = \frac{\mu - \sigma \ln T_{min}}{\gamma}$ .

The parameter values for the benchmark simulation are presented in Table 5.1. Labor input, the level of technology, and the initial resource price

Labor	$L$	1
Technological parameter	$A$	1
Resource share	$\alpha$	0.1
Substitute flow	$B$	0.5
Elasticity of marginal utility	$\theta$	0.75
Rate of time preference	$\rho$	0.02
Resource price growth rate	$r$	0.02
Initial resource price	$P_0$	1
Initial asset holdings	$a_0$	0
Planning horizon	$T$	200
Minimum time to discover	$T_{min}$	20

Table 5.1: Benchmark parameter values.

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assuming that the probability of inventing a substitute depends on the *level* of the sustained investment rate as opposed to cumulative investment.

are normalized to unity. The share of exhaustible resources in the production function is assumed to be 10%.<sup>14</sup> The value of  $\theta$  is calibrated so as to guarantee that the value of the elasticity of intertemporal consumption substitution lies in the empirically relevant range (see Epstein and Zin 1991, and Hansen and Singleton 1982, Keane and Wolpin 2001, Vissing-Jørgensen 2002). Multiple calibrations of  $\theta$  are examined, especially in the analysis of the relationship between energy dependence and investment choice. The rate of growth of the resource price in the world market, as well as the rate of time preference,  $\rho$ , are set at 2% per annum.<sup>15</sup> The length of the planning horizon,  $T$ , is assumed to be 200 years,<sup>16</sup> while the minimum average time needed to discover a substitute is 20 years. The value of  $B$  is calibrated in such a way that it no longer pays to import the resource when  $B$  becomes available:  $\partial Y / \partial B = A\alpha B^{\alpha-1} L^{1-\alpha} \leq P_0$ .

#### 5.4.1 Solution for the Optimal R&D Investment

The optimal investment rate is such that it maximizes expected lifetime welfare, given the planning horizon. Figure 5.1 plots RIC's expected welfare as a function of investment under financial autarky (thin line) and with access to credit (thick line). The maximum under AC occurs at  $m^{*AC} = 0.2646$  and under FA at  $m^{*FA} = 0.2477$ . The optimal investment rate, as well as the associated expected welfare level, are higher and the average time to discover

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<sup>14</sup>A relatively high value of the resource share is chosen in order to highlight the economy's dependency on energy input. Simulation results for alternative values of  $\alpha$  are discussed in Section 4.2.

<sup>15</sup>We ignore the possibility that RIC's investment project might alter the time path of the resource price on the global markets. Even the recent nuclear incident in Japan did not seem to have an impact on the price of non-renewable energy resources in spite of it having triggered a large drop in planned investment in nuclear power plants across a number of major economies, including Germany, Switzerland and Japan.

<sup>16</sup>Although the model is written as an infinite horizon problem, the simulations are performed for a finite horizon. The numerical algorithm is based on (5.2). However, given the finiteness of the horizon, the truncated PDF is used:  $f_\tau = \frac{\lambda(m)e^{-\lambda(m)\tau}}{1-e^{-\lambda(m)T}}$ .

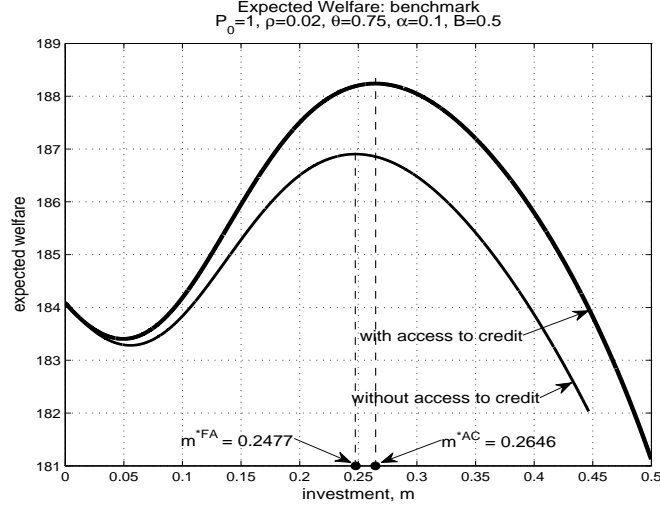


Figure 5.1: Expected welfare.

the backstop is lower under the second scenario (AC) as compared to the first scenario (FA). The result that  $m^{*AC} > m^{*FA}$  is not general, however, and depends crucially on the elasticity of intertemporal consumption substitution, as will be discussed in the next subsection. Note that due to the chosen specification of the function  $\lambda(m)$ , commitment to a relatively small amount of R&D expenditure ( $m < 0.09$  under AC and  $m < 0.11$  under FA) leads to a lower expected lifetime welfare than with no investment at all (see the drop in welfare for relatively low values of investment expenditure).

#### 5.4.2 R&D Investment and Energy Dependence

Two interesting questions emerge at this point: First, does greater dependence on resource imports raise or lower the optimal investment rate, and second, what is the role of access to foreign credit in this respect? On the one hand, greater dependence makes it more urgent to develop an alternative source of energy. On the other hand, a country that is more dependent spends a larger share of its GDP on resource imports. Its budget constraint is then tighter, making the burden of any investment project relatively heavier. In

terms of the present model, either a higher growth rate of the resource price,  $r$ , or a larger initial price of the resource,  $P_0$ , or a larger distributive share of resources in the production function,  $\alpha$ , manifest themselves in a greater dependence on resource imports. For the moment I shall consider only the two latter parameters and discuss the role of  $r$  in subsection 4.4.

The optimal response of the investment rate to an increase in energy dependence hinges to a large extent on the planner's willingness to forgo current consumption, i.e., on the elasticity of intertemporal consumption substitution (EICS for short). It has already been established analytically in Section 2 that with an infinite EICS the optimal  $m$  increases when either  $P_0$  or  $r$  rise. The response of  $m$  is different, however, when EICS is reduced to the empirically relevant range. It matters as well whether the country has access to international capital markets or not. Figure 5.2a plots  $m^*$  as a function of  $P_0$  for  $\theta = 0.25$ ,  $\theta = 0.5$ ,  $\theta = 0.75$ , and  $\theta = 0.85$  under "financial autarky" scenario. First of all, note that the slope of the relationship between  $m^*$  and  $P_0$  changes from positive to negative as  $\theta$  increases (i.e., EICS falls): the slope is positive for  $\theta = 0.25$  and  $\theta = 0.5$ , it is close to zero for  $\theta = 0.75$  and is negative for  $\theta = 0.85$ . It is even more negative for higher values of  $\theta$  (not shown in the figures). Empirical studies of EICS conclude that the relevant range is below 2 which corresponds to  $\theta > 0.5$ .<sup>17</sup> Therefore, the optimal response of the R&D investment rate is to fall as the resource price rises. The intuition here is the following. With a relatively low EICS consumer cares more about the smooth time profile of her consumption than about the total consumption over the lifetime. She is therefore less willing to forgo current consumption for the purpose of raising R&D investment which eventually may lead to an increase in consumption in the future. When the resource price rises, a con-

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<sup>17</sup>Vissing-Jørgensen (2002) estimates EICS for stock- and bondholders, distinguishing among 3 wealth groups, as well as for non-stockholders. Her estimates range from 0.29 for stockholders to 1.38 for bondholders with higher estimates for top wealth layer households and close to zero estimates for non-stockholders. See also Epstein and Zin (1991) and Hansen and Singleton (1982).

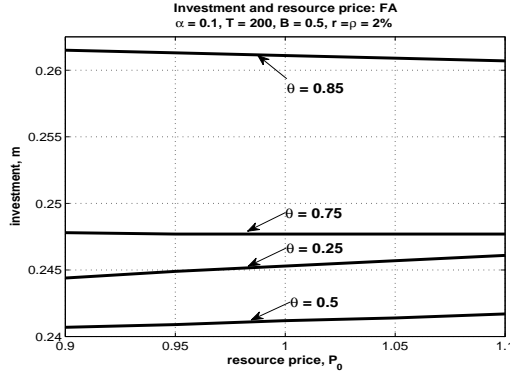


sumer with a low EICS cuts her investment expenditure in order to preserve the smooth consumption path, while a consumer with a high EICS increases her investment expenditure in order to raise the chances of having a consumption jump in the future and hence her total lifetime consumption. The same holds true when the economy has access to international lending and borrowing, as shown in figure 5.2b. The only difference is that the change in the slope occurs for a lower value of  $\theta = 0.65$  because access to financial markets facilitates consumption smoothing.

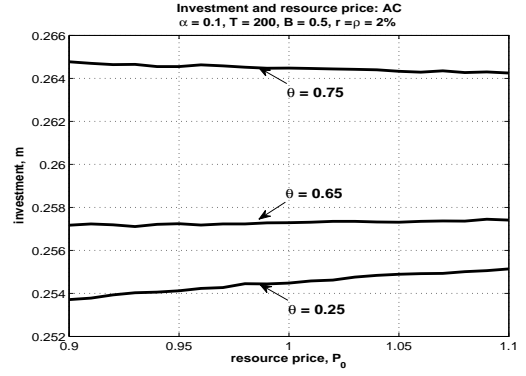
Secondly, the relationship between  $m^*$  and  $\theta$  (holding  $P_0$  fixed) is non-monotonic both under FA and AC. This can be better visualized in figure 5.2c and 5.2d where  $m^*$  is shown to be U-shaped in  $\theta$  for any given  $P_0$ . The left side of the "U" is, however, much less pronounced under AC than under FA, i.e., as EICS falls, the optimal investment rate falls by less under AC than under FA before starting to rise as  $\theta$  approaches unity. This is shown more explicitly in figure 5.2e, where the light surface corresponds to AC scenario (as in figure 5.2d), while the dark surface corresponds to FA scenario (as in figure 5.2c). For the middle range of  $\theta$ , the response of  $m$  to a decline in EICS is to fall under FA but to rise under AC. Consider two economies: one with a relatively high EICS and another with a relatively low EICS. If they operate under financial autarky, the former economy will choose a higher investment rate than the latter. If, however, they have access to capital markets, the opposite will be true.

Thirdly, the economy which has access to foreign capital markets does not necessarily invest more in renewables R&D as compared to an economy under FA. As figure 5.2e shows, for high EICS (low  $\theta$ )  $m^{*FA} > m^{*AC}$ : the dark surface lies above the light surface for  $\theta$  less than approximately 0.2. This is because without access to credit the economy can raise its future consumption only by choosing a higher investment rate. For empirically plausible EICS, however,  $m^{*AC} > m^{*FA}$ , so that having access to credit does help sustain a higher investment rate.

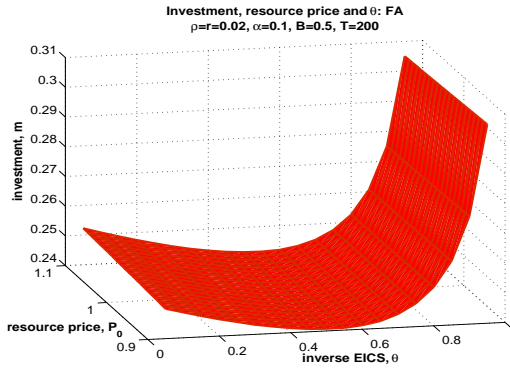
Finally, an increase in energy dependence may also be interpreted as an



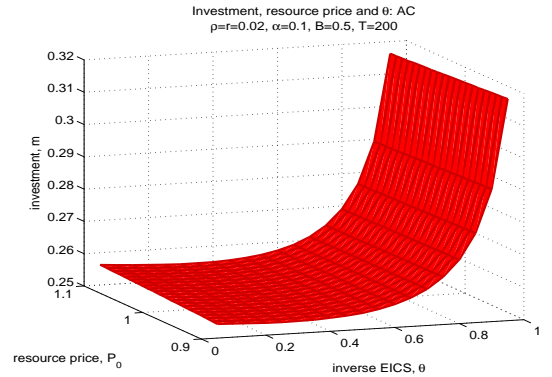
(a) Energy dependence under FA



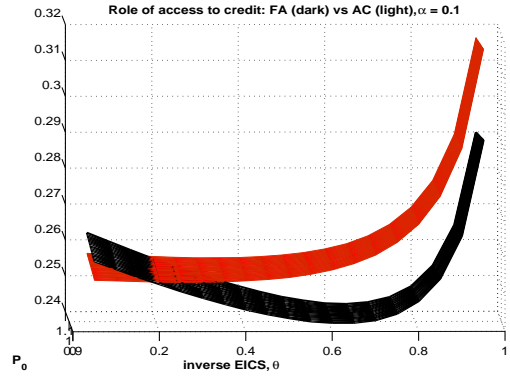
(b) Energy dependence under AC



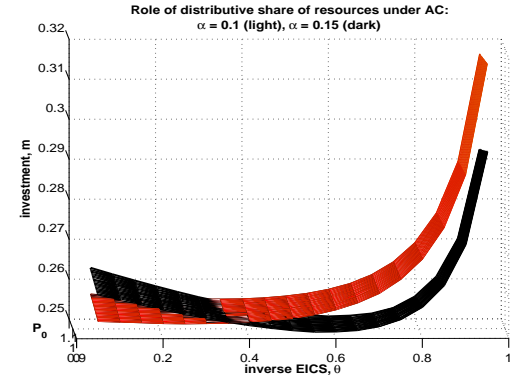
(c) Role of EICS under FA.



(d) Role of EICS under AC.



(e) Role of access to capital markets.



(f) Role of resource share in production,  $\alpha$ .

Figure 5.2: Energy dependence under FA and AC.

increase in the resource-use share in output production, i.e., a higher  $\alpha$ . The optimal response of  $m$  to an increase in  $\alpha$  (for a given  $P_0$ ) also depends on  $\theta$ , as shown in figure 5.2f. The light surface is the same as in figure 5.2d

while the dark surface corresponds to  $\alpha$  raised from 10 to 15%. Comparison of figure 5.2e with 5.2f reveals that the effect of a larger resource share in production is quite similar to losing access to credit and vice versa, having access to credit is equivalent to having a lower distributive share of energy resources in production of final goods.

To recap, under empirically plausible EICS (a) the optimal response of renewables R&D investment rate is to fall when the non-renewable-resource price rises; (b) the optimal investment rate in an economy with access to capital markets is higher than in an economy without such access; (c) having access to credit is equivalent to being less dependent on energy resources in production of final goods.

### 5.4.3 Optimal Paths of Consumption and Assets

The possibility of international lending and borrowing has important implications for the intertemporal allocation of consumption in an economy striving to achieve energy independence. Borrowing from abroad (net of interest payments) can be visualized by the gap between the " $c_t^{AC}$ " locus and the " $Y_t^n - m^{*AC}$ " locus (see the shaded area in figure 5.3a). The figure demonstrates that foreign credit has a dual purpose. It serves not only to finance the increase in the optimal investment rate but also to raise current consumption during the initial phase of the economy's planning horizon.

Note that in the present calibration the economy's rate of time preference,  $\rho$ , is identical to the rate of interest,  $r$ . In a deterministic environment, the economy's time path of consumption would have been flat. In a stochastic environment, however, the prospect of an upward jump in income results in a clockwise rotation of the consumption path. During the initial phase of the planning horizon  $c_t^{*AC}$  exceeds  $Y_t^n - m^{*AC}$ , so that  $\dot{a}_t - ra_t < 0$ . Thus, in spite of  $\rho$  being equal to  $r$ , RIC's asset position initially deteriorates. This is shown in figure 5.3b. If the substitute is never invented, consumption in figure 5.3a declines monotonically until the end of the planning horizon (dash-

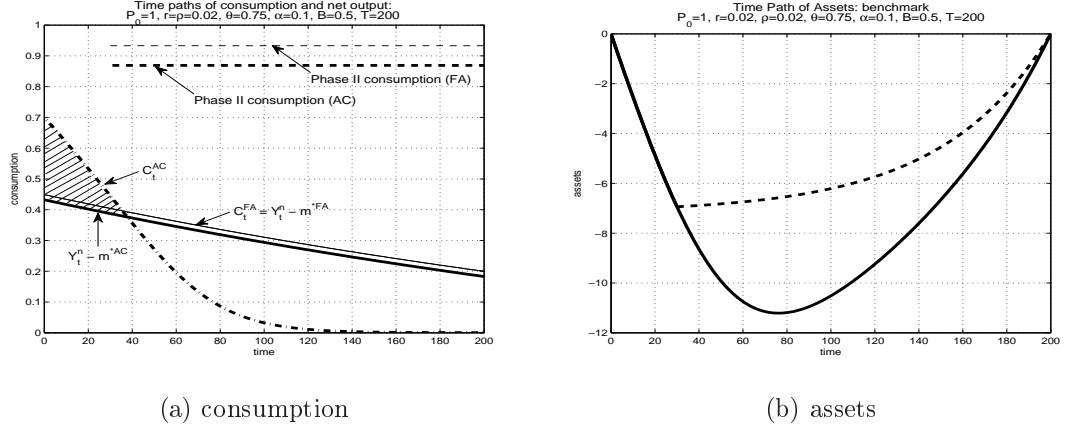


Figure 5.3: Optimal paths of consumption and net foreign asset position.

dotted line), while the net asset position in figure 5.3b exhibits a U-shaped time path with  $a_t < 0$ ,  $\forall t \in (0, T)$  and  $a_0 = a_T = 0$  (solid line).

Suppose now that the invention happens to occur at  $t = 30$ .<sup>18</sup> Under both scenarios, consumption in figure 5.3a jumps upwards (see dashed lines) and the economy switches from borrowing to repaying its debt (the dashed line in figure 5.3b). A higher value of  $B$  obviously causes a larger upward jump and a faster loan repayment (not shown in the figures).

Note that the initial consumption rate in Phase II is *higher* under FA than it is with AC. The reason is that under both scenarios the arrival of the backstop ensures a constant flow of output per unit of time but under the second scenario the economy starts Phase II with a negative foreign asset position, which must be liquidated by the end of the planning horizon. In general, the initial consumption rate in Phase II and the subsequent time path of consumption under AC depend on the parameters of the model and in particular on the difference between  $r$  and  $\rho$  (see eq. (5.17)). If  $r > \rho$  ( $r < \rho$ ), consumption in Phase II exhibits a rising (falling) time path, while  $\tilde{c}_T$  is below (above) the value obtained with  $r = \rho$ .

<sup>18</sup>With  $m^{*AC} = 0.2646$ , the probability of the discovery occurring by  $t = 30$  is equal to 72.25%.

#### 5.4.4 Role of the Cost of Credit

##### Evolution of net foreign asset position

So far the analysis proceeded under the simplifying assumption  $\rho = r$ , i.e., the economy's rate of time preference equals the world rate of interest. Variations in the cost of borrowing clearly affect RIC's optimal R&D investment rate, as well as its borrowing/lending decision. Interestingly, under specific conditions discussed below, RIC may find it optimal to have a positive net asset position (to be a lender) and at the same time maintain a relatively high R&D investment rate (above the rate under financial autarky).

Let us examine the role of the world interest rate in more detail. Figure 5.4 shows the time path of asset holdings under two alternative calibrations: a) the thin lines correspond to the case  $r = 2.5\%$  and b) the thick lines are drawn for  $r = 3\%$  per year. The solid lines illustrate the evolution of assets under the assumption that the substitute is never discovered, while the dashed schedules are drawn assuming that the discovery takes place at  $t = 60$  for case (a) and at  $t = 100$  for case (b). Note that in spite of the fact that  $r > \rho$

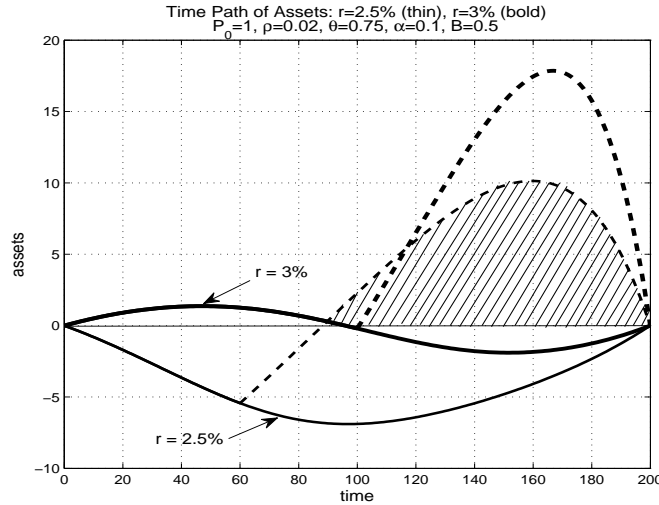


Figure 5.4: Asset position and the intertemporal terms of trade:  
 $r = 0.025$  (thin lines),  $r = 0.03$  (thick lines).

the economy is initially a net borrower under calibration (a). This is due to the effect of uncertainty, which, as we have seen in eq. (5.16), tilts clockwise the time path of consumption in Phase I and thus contributes to dissaving. Only if the substitute is eventually invented, may RIC become a lender (see the shaded area), with the length of the lending span depending negatively on the invention date and positively on EICS and on the difference between  $r$  and  $\rho$ . The later the substitute arrives, the longer the period of borrowing and the shorter the subsequent period of lending (if it exists at all). Note, in addition, that the larger is  $r$  relative to  $\rho$ , the weaker is the incentive to borrow during Phase I. Thus for higher world interest rates, the borrowing phase becomes shorter or even disappears, while the lending phase widens. Interestingly, for high enough  $r$  the borrowing phase may not necessarily occur at the beginning of the planning horizon. As illustrated by the thick solid line, for  $r = 3\%$  RIC is initially a net lender in spite of maintaining a relatively high investment rate (see figure 5.6b). The net asset position in this case exhibits a wave-shaped time profile with borrowing phase occurring at the end of the planning horizon. If  $r$  is relatively high and the invention occurs relatively late, the time profile of the net asset position peaks twice, as in the case of calibration (b) where the invention occurs at  $\tau = 100$ .

### **Invention date and debt repayment**

So far we have seen in figures 5.3b and 5.4 that the arrival of the substitute initiates repayment of the debt or further improves the asset position if it is positive: immediately after the invention the dashed lines are positively sloped and lie above the solid schedules. This, however, may not always be true. The optimal time path of the net foreign asset position after the invention depends on the relationship between  $r$  and  $\rho$ . It is clear that when  $r < \rho$ , the economy will consume at a declining rate during Phase II, i.e.,  $\hat{c}_t = \frac{r-\rho}{\theta} < 0$ . Moreover, the difference between the market rate of interest and RIC's rate of time preference also affects the *initial* consumption rate

in Phase II: the smaller (i.e., more negative) is  $r - \rho$ , the larger is  $\tilde{c}_\tau$  (see eq. (5.17)). When  $r$  is sufficiently below  $\rho$ , the economy will in fact find it optimal to start Phase II with a consumption rate in excess of its income (net of interest and imports) which entails a further deterioration of the net asset position. This is illustrated in figure 5.5, where I show the evolution of the economy's asset holdings for  $r = 0.5\%$ . As before, the solid line is drawn

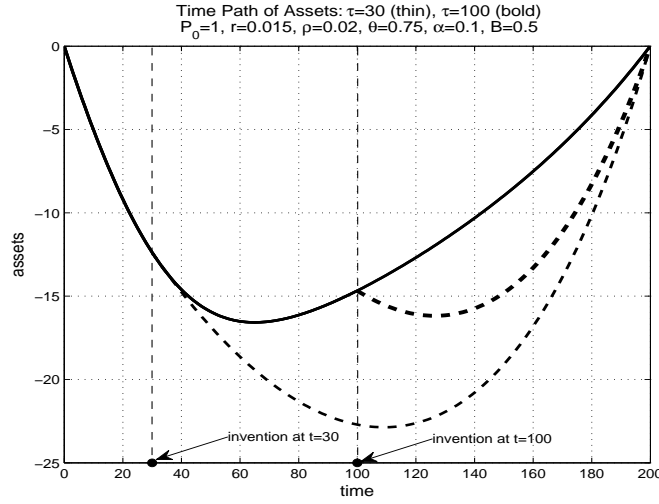


Figure 5.5: Deterioration of the asset position after the invention.

under the assumption that the substitute never arrives, while the dashed lines are drawn assuming that the invention occurs at  $t = 30$  (thin dashed line) and  $t = 100$  (thick dashed line). Given that credit is relatively cheap, the net asset position continues to deteriorate right after the invention and reaches the minimum several years later than if the substitute had never arrived. Throughout the remainder of the planning horizon the economy is more indebted than it would have been without the invention. Interestingly, the time profile of  $a_t$  may exhibit a double-trough pattern for some invention dates as, e.g., for  $\tau = 100$ . The high levels of indebtedness, equal to a multiple of the economy's GDP, are nonetheless perfectly sustainable, in the sense that RIC repays the loan to the creditors by the end of the planning horizon. This is true even if the backstop never arrives. In this case, the debt is repaid at

the expense of current consumption which falls over time.

### **Cost of credit and lifetime welfare**

Further examination of the role of the market rate of interest leads us to consider its effect on the economy's expected lifetime welfare. When access to credit is available,  $r$  affects expected welfare through two channels. The first one is the resource price: The higher the rate, the greater the rate of increase in  $P_t$  and the heavier the burden of future payments for resource imports. An additional channel emerges with the possibility of lending and borrowing. If RIC is a net borrower, a higher  $r$  implies a heavier debt burden, so that both effects contribute to a lower expected welfare. On the other hand, if RIC is a net lender, a higher  $r$  represents an improvement in its intertemporal terms of trade, contributing to higher expected welfare. Whether RIC is a borrower or a lender, is determined endogenously and depends on the structure of its preferences and its production technology, on the amount of the substitute it expects to obtain in the case of a technological breakthrough, and finally on the relationship between  $r$  and  $\rho$ . Thus, in general, the net effect of the world interest rate on the economy's expected welfare is ambiguous. It depends, in essence, on the volume of its trade in the resource market in relation to the volume of its net lending over the entire planning horizon. It is generally to be expected, however, that an economy's welfare is higher with free trade, in this case trade in the financial asset, than it is under autarky. This is illustrated in figure 5.6a, where I show RIC's expected lifetime welfare, under the optimal investment strategy, as a function of the market interest rate, holding other parameters at their benchmark levels. Under financial autarky the expected welfare declines with  $r$ , as shown by the thin line. In this case, only the effect of  $r$  on the price path of the resource impinges on welfare. With access to credit the schedule is U-shaped, reflecting the conflicting forces discussed above. Note that regardless of the value of  $r$ , the expected lifetime welfare with access to credit is always higher than without



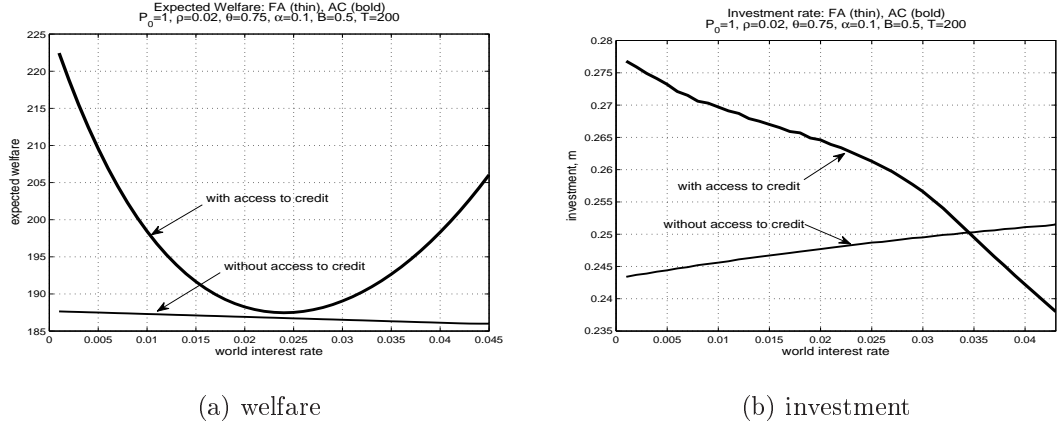


Figure 5.6: The effect of intertemporal terms of trade on welfare and investment rate.

such access. The possibility of improving the efficiency of the intertemporal allocation of resources by transacting in the international financial market has therefore an important welfare-enhancing role.

The effect of the cost of credit on the optimal R&D investment rate can be visualized in figure 5.6b. First, observe that  $m^{*FA}$  is increasing in  $r$ , while  $m^{*AC}$  is decreasing in  $r$ . This difference in the optimal response hinges on the dual role of the interest rate in the latter scenario.

Second, for high enough interest rate in relation to  $\rho$ ,  $m^{*FA}$  exceeds  $m^{*AC}$ . In other words, economies which have access to capital markets but face a relatively high cost of credit tend to choose less ambitious investment projects as compared to what they would have chosen without access to credit.

Overall, the cost of credit is an important factor influencing (a) the expected lifetime welfare, with the relationship being U-shaped; (b) the time profile of asset position and, in particular, whether it is optimal to start repaying the debt after a deterministic flow of output is ensured, or continue borrowing; and (c) the optimal sustained investment with the relationship being negative.

## 5.5 Conclusion

The paper attempts to answer two main questions: What is the optimal investment rate in an R&D project which may secure a given flow of income in the future, with the probability of the success being dependent on the investment rate? And to what extent access to capital markets matters for the investment decision? The answers to these questions are analyzed in the context of a model of a resource-importing country (RIC), which seeks to achieve energy independence by developing a renewable substitute for a non-renewable essential input. I assume that the invention of a substitute follows a stochastic process which can be influenced by the appropriate investment in R&D. The focus of the paper is on the role of access to international lending and borrowing for the optimal choice of the economy's consumption and investment rates under uncertainty. This role is highlighted by comparing the outcomes under two extreme assumptions about the economy's access to global capital markets: financial autarky vs. full access.

With access to foreign credit the economy chooses a very different time path of consumption from the one obtained under financial autarky. Due to the presence of uncertainty, i.e., a possibility of a successful R&D outcome, the economy dissaves during an initial phase of its planning horizon and runs a negative foreign asset position, even when the rate of interest is slightly higher than the rate of time preference. This type of behavior is exactly the opposite of precautionary saving in an environment with negative income shocks (see, e.g., Toche (2005) for the case of a job loss).

When it comes to the optimal choice of the R&D investment rate, having access to capital markets does not necessarily imply that the economy systematically invests more than it does without such access. The outcome depends crucially on the value of the elasticity of intertemporal consumption substitution (EICS). Numerical simulations show, however, that for empirically relevant range of EICS, R&D investment rate with access to credit

markets always exceeds the investment rate under financial autarky.

Another key element influencing the optimal choice of the R&D investment rate is the economy's dependence on foreign energy sources, as measured by the share of GDP absorbed by the expenditure on resource imports. In the context of the present model, energy dependence is determined by the market price of the resource and the distributive share of energy in the production of final goods. An increase in the resource price may either boost or decrease the investment rate depending on EICS. The numerical results show that in the empirically relevant range of values for EICS an increase in the resource price leads to a lower optimal investment rate. This result holds regardless of whether or not the economy has access to borrowing and lending. Having access to global capital markets, however, is shown to be equivalent to a reduction in the distributive share of energy resources in production of final goods.

Several interesting results emerge when we look at what role the cost of credit,  $r$ , plays in determining the optimal investment choice and the economy's net foreign asset position (NFA). First, it is shown that, depending on the relationship between  $r$  and the rate of time preference  $\rho$ , RIC may be either a borrower or a lender, and in particular, the lending phase may precede the phase of borrowing. Second, a successful R&D outcome causes an improvement in the NFA when  $r$  is not too low in relation to  $\rho$  but a *deterioration* in the NFA for low enough interest rates. Third, the economy's expected lifetime welfare with access to credit always exceeds the one obtained under financial autarky, regardless of the value of  $r$ . Moreover, the welfare with access to credit is U-shaped in  $r$  due to the dual role of the latter in the resource and capital markets. Finally, the optimal investment rate responds differently to variations in  $r$  depending on whether access to credit is available or not: it is an increasing function of  $r$  under financial autarky but a *decreasing* function of  $r$  under openness.

The present analysis motivates the desire to invent a substitute for a non-renewable resource by its increasing market price and thus increasing

dependence on energy imports. Introducing other motivations for a switch from non-renewable to renewable sources of energy, such as an objective to meet a specific climate-policy target, would enrich the analysis even further. Assuming that the social planner dislikes pollution and the backstop is a clean energy source, there would be an additional incentive to invest in R&D.

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## 5.6 Appendix

### 5.6.1 Transforming a Stochastic Control Problem into a Deterministic Control Problem

In the case of financial autarky the optimization problem is to maximize

$$E_\tau \left\{ \int_0^\tau u(c_t) e^{-\rho t} dt + \int_\tau^\infty u(\tilde{c}_t) e^{-\rho t} dt \right\}, \quad (5.21)$$

subject to  $c_t = Y_t^n - m_t$  and  $\tilde{c}_t = \bar{Y}$ , where  $E_\tau$  denotes the expectation operator with respect to the distribution of the arrival date. Given that

$$\mathcal{P}[\tau \in (t, t + dt) | \tau \geq t] = q(m_t) dt + o(dt),$$

the elementary probability on the interval  $(t, t + dt)$  is given by  $q(m_t) e^{-\int_0^t q(m_s) ds} dt$ .

Then (5.21) can be rewritten as

$$\int_0^\infty \left\{ \int_0^t u(c_s) e^{-\rho s} ds + \int_t^\infty u(\tilde{c}_s) e^{-\rho s} ds \right\} q(m_t) e^{-\int_0^t q(m_s) ds} dt. \quad (5.22)$$

Since the consumption rate after the arrival of the backstop is constant at  $\bar{Y}$ , the last term in the curly braces equals to  $u(\bar{Y}) \frac{e^{-\rho t}}{\rho}$ , and (5.23) can be written as

$$\int_0^\infty \left\{ \int_0^t u(c_s) e^{-\rho s} ds \right\} q(m_t) e^{-\int_0^t q(m_s) ds} dt + \frac{u(\bar{Y})}{\rho} \int_0^\infty q(m_t) e^{-\rho t - \int_0^t q(m_s) ds} dt. \quad (5.23)$$

Defining  $\mathcal{U}(t) = \int_0^t u(c_s) e^{-\rho s} ds$  and  $\mathcal{V}(t) = -e^{-\int_0^t q(m_s) ds}$ , we can apply integration by parts to the first term to obtain:

$$\int_0^\infty \left\{ \int_0^t u(c_s) e^{-\rho s} ds \right\} q(m_t) e^{-\int_0^t q(m_s) ds} dt = \quad (5.24)$$

$$\int_0^\infty \mathcal{U}(t) d\mathcal{V}(t) = \quad (5.25)$$

$$\mathcal{U}(t) \mathcal{V}(t) - \int_0^\infty \mathcal{V}(t) d\mathcal{U}(t) = \quad (5.26)$$

$$- \int_0^t u(c_s) e^{-\rho s} ds \left[ e^{-\int_0^t q(m_s) ds} \right] + \int_0^\infty e^{-\int_0^t q(m_s) ds} u(c_t) e^{-\rho t} dt. \quad (5.27)$$



The term  $\mathcal{U}(t)\mathcal{V}(t)$  is zero in the limit as  $t$  goes to infinity since  $\int_0^t u(c_s)e^{-\rho s}ds < \infty$  and  $\int_0^\infty q(m_s)ds = \infty$ . Then the original objective in (5.23) becomes

$$\begin{aligned} & \int_0^\infty e^{-\int_0^t q(m_s)ds} u(c_t) e^{-\rho t} dt + \frac{u(\bar{Y})}{\rho} \int_0^\infty q(m_t) e^{-\rho t - \int_0^t q(m_s)ds} dt = \\ & = \int_0^\infty \left\{ u(c_t) + q(m_t) \frac{u(\bar{Y})}{\rho} \right\} e^{-\rho t - \int_0^t q(m_s)ds} dt. \end{aligned} \quad (5.28)$$

Defining an auxiliary state variable  $z_t \equiv \int_0^t q(m_s)ds$  with  $\dot{z}_t \equiv \frac{dz}{dt} = q(m_t)$  and  $z_0 = 0$ , the objective function (5.28) becomes

$$\int_0^\infty \left\{ u(c_t) + q(m_t) \frac{u(\bar{Y})}{\rho} \right\} e^{-\rho t - z_t} dt, \quad (5.29)$$

which is used to construct the Hamiltonian (5.4) in the text.

## 5.6.2 Optimal Investment with Open Access to International Lending and Borrowing

The optimal control problem pertaining to phase II is:

$$\max_{\tilde{c}_t} \int_\tau^\infty u(\tilde{c}_t) e^{-\rho(t-\tau)} dt$$

subject to

$$\dot{a}_t = B^\alpha L^{1-\alpha} - \tilde{c}_t + r a_t, \quad \forall t > \tau. \quad (5.30)$$

The current-value Hamiltonian may be written as

$$H = u(\tilde{c}_t) + \mu_t [B^\alpha L^{1-\alpha} - \tilde{c}_t + r a_t]$$

and the first order conditions

$$\tilde{c}_t : \quad u'(\tilde{c}_t) - \mu_t = 0, \quad (5.31)$$

$$a_t : \quad \mu_t r = \rho - \dot{\mu}. \quad (5.32)$$

Differentiating eq. (5.31) with respect to time and inserting the result in (5.32) yields the standard Keynes-Ramsey rule

$$\hat{\tilde{c}}_t = \frac{r - \rho}{\theta}, \quad \forall t > \tau$$

and therefore the consumption path

$$\tilde{c}_t = \tilde{c}_\tau e^{\frac{r-\rho}{\theta}(t-\tau)}.$$

Combining this with the budget constraint (5.30) allows to solve for the consumption rate right after the discovery takes place,  $\tilde{c}_\tau$ , and for the time path of asset holdings:

$$\tilde{c}_\tau = \left(r - \frac{r-\rho}{\theta}\right) \left(a_\tau + \frac{B^\alpha L^{1-\alpha}}{r}\right), \quad (5.33)$$

$$a_t = a_\tau e^{\frac{r-\rho}{\theta}(t-\tau)} + \frac{B^\alpha L^{1-\alpha}}{r} \left(e^{\frac{r-\rho}{\theta}(t-\tau)} - 1\right). \quad (5.34)$$

The the maximized discounted (time- $\tau$ ) welfare in Phase II is

$$\Phi(a_\tau) = \int_\tau^\infty \frac{\tilde{c}_t^{1-\theta}}{1-\theta} e^{-\rho(t-\tau)} dt = u(\tilde{c}_\tau) \left(r - \frac{r-\rho}{\theta}\right)^{-1}.$$

The Hamiltonian, associated with the RIC's original optimization problem may be written as

$$H = \{u(c_t) + \lambda(m)\Phi(a_t)\} e^{-\rho t - z_t} + \eta_t (ra_t + R_t^\alpha L^{1-\alpha} - c_t - P_t R_t - m) + \nu_t \lambda(m),$$

where  $\eta_t$  is the co-state variable associated with the constraint (5.11) and  $z_t$  is the auxiliary state variable, such that  $\dot{z}_t = \lambda(m)$ . The optimality conditions are

$$R_t : \quad \eta_t \left( \frac{\partial F_t}{\partial R_t} - P_t \right) = 0, \quad (5.35)$$

$$c_t : \quad u(c_t) e^{-\rho t - z_t} - \eta_t = 0, \quad (5.36)$$

$$m : \quad \lambda'(m) \Phi(a_t) e^{-\rho t - z_t} - \eta_t + \nu_t \lambda'(m) = 0, \quad (5.37)$$

$$a_t : \quad \lambda(m) \frac{\partial \Phi_t}{\partial a_t} e^{-\rho t - z_t} + r \eta_t = -\dot{\eta}_t, \quad (5.38)$$

$$z_t : \quad -\left(u(c_t) + \lambda(m) \Phi(a_t)\right) e^{-\rho t - z_t} = -\dot{\nu}_t. \quad (5.39)$$

Combining (5.36) with (5.38) yields the Keynes-Ramsey rule under uncertainty:

$$\theta \hat{c}_t = r - \rho - \lambda(m) \left[ 1 - \frac{u'(\tilde{c}_t)}{u'(c_t)} \right],$$

where I used  $u'(\tilde{c}_t) = \frac{\partial \Phi_t}{\partial a_t}$ . Isolating  $\nu_t$  from (5.37), differentiating with respect to time and inserting the result in (5.39) yields:

$$u(c_t) = \frac{u''(c_t)\dot{c}_t - u'(c_t)(\rho + \lambda(m))}{\lambda'(m)} + \rho\Phi(a_t) - u'(\tilde{c}_t)\dot{a}_t.$$

The expression in the square brackets can be rewritten in terms of consumption growth rate and then combined with the Keynes-Ramsey rule, so that we get equation (5.18) in the text:

$$\lambda'(m) [\rho\Phi(a_t) - u(c_t) - u'(\tilde{c}_t)\dot{a}_t] = u'(c_t)r + \lambda u'(\tilde{c}_t).$$

## Chapter 6

# Environmental Regulation and Compliance

### 6.1 Introduction

There is a global agreement that efforts should be made to deal with climate change. However, there is no unanimous view on how the burden of these efforts should be shared between developed and developing countries. Many advanced countries, and notably the European Union, already have in place various schemes to control their emissions, while none of the developing countries do. The reasons are multiple, including weak environmental policies and legislation, insufficient financing and, most importantly, lower priority attached to issues related to climate change when compared to poverty reduction, standard of living and health improvement and economic growth. This paper examines sets of conditions which should be satisfied in order to induce the developing economies to voluntarily accept environmental standards.

Given the asymmetry in the climate legislation, some developed countries fear the loss of competitiveness of their energy-intensive industries: A good produced by their domestic firms becomes more expensive as the costs of production rise when emissions permits need to be purchased. On several occasions European policymakers expressed their readiness to apply trade

restrictions on countries which do not apply emissions standards similar to theirs. For instance, Manuel Barroso in his interview to *The Times* said: "We do not want to put our energy-intensive industries in a situation of disadvantage in competition terms, that is why we will have measures that we are ready to take if there is not a global climate agreement" (March 2008). Former French president Nicolas Sarkozy said that EU must examine the possibility of "taxing products imported from countries that do not comply with the Kyoto protocol. We have imposed environmental standards on our producers. It is not normal that their competitors should be completely exempted...Environmental dumping is not fair" (October 2007). In particular, the so-called "border-adjustment measures" were a hot discussion topic and were viewed as indispensable for a climate legislation to pass in the US Congress. "Only sticks" approach, however, may turn out not to be feasible, as it may fail to comply with WTO rules. For example, according to WTO agreement, trade provisions should be preceded by major efforts to negotiate with partners within a reasonable timeframe. Thus proposed measures may not only include "sticks" but also "carrots", as in the Montreal Protocol (1987) or "clean development mechanism", where trade measures were accompanied by financing arrangements and technology transfers. Developing countries, however, will have to demonstrate a "meaningful" commitment (Zhang 2009), i.e., they are not required to comply with environmental regulations immediately but should take some actions towards compliance at some future date. This is akin to the "grace" period granted to LDCs under the Montreal Protocol.

The effectiveness of "sticks and carrots" policy is yet to be assessed but undoubtedly one cannot do so without first taking the perspective of a less developed country (LDC). Certain conditions must be in place in order for LDC to comply voluntarily with the regulation, otherwise it will not. The purpose of the study is to establish the minimum conditions for voluntary compliance and to analyze the LDC's optimal response to any changes in the conditions it faces. I purposely do not model any restrictive/retaliative measures, such as

trade restrictions or environmental taxes, since their acceptable legal format, for example compatible with WTO rules, has not yet been clearly established. By contrast, I focus on supporting/stimulating measures, such as monetary transfers. More specifically, I analyze two types of regulation: One where a predefined transfer is initiated on the date of compliance with emissions target; and the other where the amount transferred is tied to emissions-control effort. The main results of the paper is that offering one or the other option is inefficient. The chances that an LDC complies voluntarily with environmental standards are higher when a menu of options is on the table. The direct implication of this results is that the number and/or diversity of countries willing to comply with environmental standards is also higher when a variety of alternatives is available instead of just one regulation type.

The next Section sets up the model by first describing an economy which is not yet subjected to any environmental regulation. Then two regulation types are introduced. Section 3 analyzes the conditions for voluntary compliance. Section 4 is devoted to policy analysis, while Section 5 concludes.

## 6.2 The Model

### 6.2.1 Unconstrained Economy

Consider an economy which produces a single consumption good with the aid of capital according to the production function  $Q_t = Q(K_t)$ ,  $Q'(K_t) > 0$ . Output can be either consumed or invested. As a by-product of production and consumption processes emissions are released into the atmosphere. A technology for addressing the emissions problem exists. It requires, however, capital investment, with the effectiveness of emissions control being positively related to the stock of equipment utilized for that purpose. Thus the flow of emissions at time  $t$  is given by

$$E_t = \phi_c c_t + \phi_k K_t - \phi_x X_t + \bar{E}, \quad (6.1)$$

where  $c_t$  stands for per-capita consumption,  $K_t$  for physical capital stock,  $X_t$  is the economy's stock of capital specifically designed for emissions control and  $\phi_c$ ,  $\phi_k$ , and  $\phi_x$  are positive constants (assumed to be less than unity) which measure pollution intensity of consumption, pollution intensity of physical capital, and abatement intensity of pollution-control capital, respectively. The parameter  $\bar{E}$  stands for the global pollution and is taken as given. Without loss of generality it will be normalized to zero in the rest of the analysis. Let us assume that the technology for producing the specific pollution-control equipment exists but is not available in the economy. The equipment must therefore be imported from abroad at the price  $P$  per unit, with the consumption good being the numeraire. The pollution-control capital is accumulated in a standard way:

$$\dot{X}_t = I_t, \quad X_0 \text{ given}, \quad (6.2)$$

where  $I_t$  is the investment rate in pollution control.

The economy is inhabited by one infinitely-lived representative individual who derives utility from consumption and suffers disutility of pollution. The utility function  $u(c_t, E_t)$  is assumed to be increasing and concave in  $c_t$  and decreasing and concave in  $E_t$ , i.e.,  $\frac{\partial u}{\partial c_t} > 0$ ,  $\frac{\partial^2 u}{\partial c_t^2} < 0$ ,  $\frac{\partial u}{\partial E_t} < 0$ ,  $\frac{\partial^2 u}{\partial E_t^2} < 0$ , and  $\frac{\partial^2 u}{\partial c_t \partial E_t} \leq 0$ .

The objective is:

$$\max_{c_t, E_t} \int_0^\infty u(c_t, E_t) e^{-\rho t} dt, \quad (6.3)$$

subject to the physical capital accumulation constraint

$$\dot{K}_t = Q(K_t) - c_t - I_t P, \quad K_0 \text{ given}, \quad (6.4)$$

the pollution control capital accumulation constraint (6.2), and equation (6.1) describing the flow of emissions. The rate of time preference is a constant  $\rho$ .

The current-value Hamiltonian associated with the optimization program can be written as

$$H = u(c_t, E_t) + \lambda_t [Q(K_t) - c_t - I_t P] + \mu_t I_t +$$

$$+\eta_t [\phi_c c_t + \phi_k K_t - \phi_x X_t - E_t].$$

The optimality conditions are (time subscripts are suppressed for notational convenience):

$$c : \quad \frac{\partial u}{\partial c} - \lambda + \eta \phi_c = 0, \quad (6.5)$$

$$E : \quad \frac{\partial u}{\partial E} - \eta = 0, \quad (6.6)$$

$$I : \quad -\lambda P + \mu = 0, \quad (6.7)$$

$$K : \quad \lambda Q'(K) + \eta \phi_k = \rho \lambda - \dot{\lambda}, \quad (6.8)$$

$$X : \quad -\eta \phi_x = \rho \mu - \dot{\mu}, \quad (6.9)$$

and the transversality condition  $\lim_{t \rightarrow \infty} K_t e^{-\rho t} = 0$ .

In order to obtain an analytical solution to the model, the following functional forms are assumed:

- production function of  $AK$  type:  $Q_t = AK_t$ , where  $A > 0$  is a technological parameter;
- a separable utility function which is logarithmic in consumption and quadratic in emissions:  $u(c_t, E_t) = \ln c_t - \frac{1}{2} E_t^2$  (see, e.g., Withagen (1995) for a similar specification).

Given these functional forms, we have  $Q'(K_t) = A$ ,  $\frac{\partial u}{\partial c_t} = \frac{1}{c_t}$ ,  $\frac{\partial u}{\partial E_t} = -E_t$ .

Then it follows from (6.8) - (6.9) that

$$A + \frac{\eta \phi_k}{\lambda} = -\frac{\eta \phi_x}{\lambda P}$$

or

$$\frac{\eta}{\lambda} = -\frac{A}{\phi_k + \phi_x / P} \equiv -\gamma.$$

Hence, using (6.5) and (6.6),

$$\frac{E}{1/c - \phi_c E} = \gamma \Rightarrow E(1 + \gamma \phi_c) = \gamma / c. \quad (6.10)$$

This last expression leads to two observations. First, the growth rate of emissions is the negative of the growth rate of consumption. Second, by



time-differentiating the above expression and inserting the result in (6.8) we get

$$\frac{\dot{c}}{c} = \frac{\gamma\phi_x}{P} - \rho \equiv \psi \Rightarrow c_t = c_0 e^{\psi t}. \quad (6.11)$$

For expositional convenience I defined the growth rate of consumption as  $\psi$  and assume that  $\psi > 0$ . The growth rate depends positively on the productivity of physical capital,  $A$ , and on the abatement intensity,  $\phi_x$ . It depends negatively on the price of pollution-control equipment,  $P$ , and the capital polluting intensity,  $\phi_k$ . The polluting intensity of consumption,  $\phi_c$ , affects only consumption level but not the growth rate. If physical capital were not polluting, i.e.,  $\phi_k = 0$ , we would obtain the standard Keynes-Ramsey growth rate equal to the difference between the marginal product of capital and the pure rate of time preference, i.e.,  $\psi = A - \rho$ , given the assumed log-preferences.

Since the growth rate of emissions is the negative of the growth rate of consumption, emissions decline at the rate  $\psi$ :

$$E_t = E_0 e^{-\psi t}. \quad (6.12)$$

Combining the time paths of consumption and emissions with eq. (6.1) allows to obtain the relationship between the two capital stocks:

$$X_t = \frac{1}{\phi_x} [\phi_c c_0 e^{\psi t} + \phi_k K_t - E_0 e^{-\psi t}] \quad (6.13)$$

Differentiation of (6.13) with respect to time yields the time path of investment rate in pollution control:

$$I_t = \frac{1}{\phi_x} [\psi \phi_c c_0 e^{\psi t} + \phi_k \dot{K}_t + \psi E_0 e^{-\psi t}]. \quad (6.14)$$

Substituting (6.11) and (6.14) into the capital accumulation constraint (6.4) yields:

$$\dot{K}_t = AK_t - c_0 e^{\psi t} - \frac{P}{\phi_x} [\phi_c \psi c_0 e^{\psi t} + \phi_k \dot{K}_t + \psi E_0 e^{-\psi t}]$$

and thus

$$\dot{K}_t = \frac{A\phi_x}{\phi_x + P\phi_k} K_t - \frac{c_0(\phi_x + P\psi\phi_c)}{\phi_x + P\phi_k} e^{\psi t} - \frac{P\psi E_0}{\phi_x + P\phi_k} e^{-\psi t}.$$

Since the optimal paths of emissions and consumption are linked by (6.10), we can express  $E_0$  in terms of  $c_0$  as  $E_0 = \frac{\gamma}{(1+\gamma\phi_c)c_0}$ . Then, by integrating the above differential equation and applying the transversality condition, we can pin down the initial consumption rate. For convenience, define  $\delta_c \equiv \frac{c_0(\phi_x + P\psi\phi_c)}{\phi_x + P\phi_k}$  and  $\delta_E \equiv \frac{E_0\psi P}{\phi_x + P\phi_k}$  and note that  $\frac{A\phi_x}{\phi_x + P\phi_k} = \psi + \rho$ .

$$\begin{aligned} \dot{K}_t - (\psi + \rho)K_t &= -\delta_c e^{\psi t} - \delta_E e^{-\psi t}, \\ \int_0^\infty \left( \dot{K}_t - (\psi + \rho)K_t \right) e^{-(\psi+\rho)t} dt &= -\delta_c \int_0^\infty e^{-\rho t} dt - \delta_E \int_0^\infty e^{-(2\psi+\rho)t} dt, \\ K_s e^{-(\psi+\rho)s} \Big|_0^\infty &= \delta_c \frac{e^{-\rho s}}{\rho} \Big|_0^\infty + \delta_E \frac{e^{-(2\psi+\rho)s}}{2\psi + \rho} \Big|_0^\infty, \\ K_0 &= \frac{\delta_c}{\rho} + \frac{\delta_E}{2\psi + \rho}. \end{aligned}$$

Substituting the expressions for  $\delta_c$  and  $\delta_E$  yields a quadratic equation in  $c_0$ :

$$ac_0^2 - bc_0 + d = 0, \quad \text{with} \quad (6.15)$$

$$a \equiv \frac{\phi_x + P\psi\phi_c}{(\phi_x + P\phi_k)\rho}, \quad b \equiv K_0, \quad d \equiv \frac{\psi P \gamma}{(\phi_x + P\phi_k)(1 + \gamma\phi_c)(2\psi + \rho)}.$$

In general, (6.15) has two real roots if and only if  $b^2 - 4ad > 0$ , one real root if  $b^2 - 4ad = 0$ , and two complex roots if  $b^2 - 4ad < 0$ . For the rest of the analysis I assume that the initial capital stock is sufficiently large to guarantee that  $b^2 - 4ad \geq 0$ . If strict equality holds, then the solution for  $c_0$  is unique and equal to  $\frac{b}{2a}$ . If strict inequality holds, then there exist two (positive) values of  $c_0$ , one which is higher than the unique value and the other which is lower. These values can be compactly written as  $\frac{b \pm \sqrt{b^2 - 4ad}}{2a}$ . For simplicity of exposition, let us focus on the unique solution for  $c_0$ :

$$c_0 = \frac{K_0(\phi_x + P\phi_k)\rho}{2(\phi_x + P\psi\phi_c)}. \quad (6.16)$$

Knowing the initial consumption rate, the time path of the physical capital

stock can now be completely characterized:

$$\begin{aligned}
\int_0^t \left( \dot{K}_t - (\psi + \rho) K_t \right) e^{-(\psi + \rho)t} dt &= -\delta_c \int_0^t e^{-\rho t} dt - \delta_E \int_0^t e^{-(2\psi + \rho)t} dt, \\
K_s e^{-(\psi + \rho)s} \Big|_0^t &= \delta_c \frac{e^{-\rho s}}{\rho} \Big|_0^t + \delta_E \frac{e^{-(2\psi + \rho)s}}{2\psi + \rho} \Big|_0^t, \\
K_t e^{-(\psi + \rho)t} - K_0 &= -\delta_c \frac{1 - e^{-\rho t}}{\rho} - \delta_E \frac{1 - e^{-(2\psi + \rho)t}}{2\psi + \rho}, \\
K_t &= K_0 e^{(\psi + \rho)t} - \delta_c \frac{e^{(\psi + \rho)t} - e^{\psi t}}{\rho} - \delta_E \frac{e^{(\psi + \rho)t} - e^{-\psi t}}{2\psi + \rho},
\end{aligned}$$

and substituting the optimal  $c_0$  into  $\delta_c$  and  $\delta_E$  we finally obtain:

$$K_t = \frac{K_0(e^{(\psi + \rho)t} + e^{\psi t})}{2} - \frac{2\gamma\psi P(\phi_x + P\psi\phi_c)(e^{(\psi + \rho)t} - e^{-\psi t})}{(\phi_x + P\phi_k)^2(1 + \gamma\phi_c)(2\psi + \rho)K_0\rho}. \quad (6.17)$$

The time path of the pollution-control capital can be found by substituting (6.16) and (6.17) into (6.13).

The present discounted value of lifetime welfare is given by

$$W = \int_0^\infty \left[ \ln c_t - \frac{1}{2} E_t^2 \right] e^{-\rho t} dt = \frac{\ln c_0}{\rho} + \frac{\psi}{\rho^2} - \left( \frac{\gamma}{c_0(1 + \gamma\phi_c)} \right)^2 \frac{1}{2(\rho + 2\psi)}.$$

## 6.2.2 Economy Subjected to Environmental Regulation

Let us now examine the optimal behavior of the economy when an environmental regulation is imposed on it. Below we consider two types of regulation.

### Type I Regulation

Type I regulation states that the country must reduce its emissions to a given level  $\varepsilon$  by a given date  $\tau$ . The emissions reduction must follow a prespecified plan such that the rate of emissions decline must be equal to a given constant  $\theta$  - this captures the notion of "meaningful commitment". From time  $\tau$  onwards emissions must not exceed  $\varepsilon$ . If the economy complies with the regulation, it will receive a flow of aid (or monetary compensation) equal to the amount  $F$

on day  $\tau$  and subsequently  $Fe^{-g(t-\tau)}$ , i.e., the compensation will be decreasing at the rate  $g$ .<sup>1</sup>

Suppose the economy wishes to comply with the regulation. Then its optimal programme will consist of two phases: Phase I which lasts from time 0 to time  $\tau$ , and Phase II which lasts from  $\tau$  onwards. Let us first analyze Phase II.

### PHASE II

The optimization problem is to

$$\max_{\tilde{c}_t} \int_{\tau}^{\infty} u(\tilde{c}_t, \varepsilon) e^{-\rho t} dt$$

subject to

$$\begin{aligned} \dot{K}_t &= Q(K_t) - \tilde{c}_t - P\tilde{I}_t + Fe^{-g(t-\tau)}, \\ \dot{X}_t &= \tilde{I}_t, \\ \phi_c \tilde{c}_t + \phi_k K_t - \phi_x X_t &= \varepsilon, \end{aligned} \tag{6.18}$$

where a tilde over a control variable indicates that the variable pertains to Phase II. The Hamiltonian may be written as:

$$H = u(\tilde{c}_t, \varepsilon) + \lambda_t [Q(K_t) - \tilde{c}_t - \tilde{I}_t P + Fe^{-g(t-\tau)}] + \mu_t \tilde{I}_t + \eta_t [\phi_c \tilde{c}_t + \phi_k K_t - \phi_x X_t - \varepsilon].$$

The optimality conditions are (time subscripts are suppressed for notational convenience):

$$\tilde{c} : \quad \frac{\partial u}{\partial \tilde{c}} - \lambda + \eta \phi_c = 0, \tag{6.19}$$

$$\tilde{I} : \quad -\lambda P + \mu = 0, \tag{6.20}$$

$$K : \quad \lambda Q'(K) + \eta \phi_k = \rho \lambda - \dot{\lambda}, \tag{6.21}$$

$$X : \quad -\eta \phi_x = \rho \mu - \dot{\mu}, \tag{6.22}$$

and the transversality condition  $\lim_{t \rightarrow \infty} K_t e^{-\rho t} = 0$ .

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<sup>1</sup>The decline of the flow of aid in time can be rationalized by the limited commitment of the advanced countries but also by the development process in the less advanced countries.

Following the same steps as in the previous subsection, we obtain:

$$\frac{\dot{\tilde{c}}}{\tilde{c}} = \frac{\gamma\phi_x}{P} - \rho \equiv \psi \Rightarrow \tilde{c}_t = \tilde{c}_\tau e^{\psi(t-\tau)}, \quad (6.23)$$

so that consumption grows at the rate  $\psi$ , assumed positive. Since emissions are constrained by the environmental regulation, the two capital stocks must be related as:

$$X_t = \frac{1}{\phi_x} [\phi_k K_t + \phi_c \tilde{c}_\tau e^{\psi(t-\tau)} - \varepsilon]$$

and thus the investment rate in pollution control is given by

$$\tilde{I}_t = \dot{X}_t = \frac{1}{\phi_x} [\phi_k \dot{K}_t + \psi \phi_c \tilde{c}_\tau e^{\psi(t-\tau)}].$$

Using this in (6.18) yields:

$$\dot{K}_t = (\psi + \rho)K_t - \tilde{c}_\tau \frac{\phi_x + P\phi_c\psi}{\phi_x + P\phi_k} e^{\psi(t-\tau)} + \frac{F\phi_x}{\phi_x + P\phi_k} e^{-g(t-\tau)}.$$

Integrating the above differential equation from  $\tau$  to infinity and applying the transversality condition allows to solve for the initial consumption rate of Phase II:

$$\tilde{c}_\tau = \left( K_\tau + \frac{\tilde{F}}{\psi + \rho + g} \right) \frac{\rho}{\tilde{\delta}_c}, \quad (6.24)$$

where  $\tilde{F} \equiv \frac{F\phi_x}{\phi_x + P\phi_k}$  and  $\tilde{\delta}_c \equiv \frac{\phi_x + P\phi_c\psi}{\phi_x + P\phi_k}$  and  $K_\tau$  is the capital stock inherited from Phase I to which we now turn.

### PHASE I

The optimization problem is to

$$\max_{c_t} \int_0^\tau u(c_t, \varepsilon e^{\theta(\tau-t)}) e^{-\rho t} dt$$

subject to

$$\dot{K}_t = Q(K_t) - c_t - PI_t, \quad (6.25)$$

$$\dot{X}_t = I_t, \quad (6.26)$$

$$\phi_c c_t + \phi_k K_t - \phi_x X_t = \varepsilon e^{\theta(\tau-t)}. \quad (6.27)$$

The Hamiltonian is then

$$H = u(c_t, \varepsilon e^{\theta(\tau-t)}) + \lambda_t [Q(K_t) - c_t - PI_t] + \mu_t I_t + \eta_t [\phi_c c_t + \phi_k K_t - \phi_x X_t - \varepsilon e^{\theta(\tau-t)}]$$

and the first-order conditions

$$c : \quad \frac{\partial u}{\partial c} - \lambda + \eta \phi_c = 0, \quad (6.28)$$

$$I : \quad -\lambda P + \mu = 0, \quad (6.29)$$

$$K : \quad \lambda Q'(K) + \eta \phi_k = \rho \lambda - \dot{\lambda}, \quad (6.30)$$

$$X : \quad -\eta \phi_x = \rho \mu - \dot{\mu}. \quad (6.31)$$

This set of conditions allows to solve for the growth rate of consumption in Phase I:

$$\frac{\dot{c}}{c} = \frac{\gamma \phi_x}{P} - \rho \equiv \psi \Rightarrow c_t = c_0 e^{\psi t}, \quad (6.32)$$

so that consumption grows at the same rate  $\psi$  in both phases. Then, using eqs. (6.27) and (6.25), the time path of the physical capital stock can be obtained:

$$K_t = K_0 e^{(\psi+\rho)t} - \delta_c \frac{e^{(\psi+\rho)t} - e^{\psi t}}{\rho} - \delta_\varepsilon \frac{e^{(\psi+\rho)t} - e^{-\theta t}}{\theta + \psi + \rho}, \quad (6.33)$$

where  $\delta_\varepsilon \equiv \frac{P\theta\varepsilon e^{\theta\tau}}{\phi_x + P\phi_k}$  and  $\delta_c \equiv \frac{c_0(\phi_x + P\psi\phi_c)}{\phi_x + P\phi_k}$  is defined as before. Since consumption grows continuously at the same rate in both phases, we have  $\tilde{c}_\tau = c_\tau = c_0 e^{\psi\tau}$ . We can therefore combine eqs. (6.24) and (6.33), evaluated at time  $t = \tau$ , to solve for the optimal initial consumption rate:

$$c_0^I = \frac{\rho}{\phi_x + P\psi\phi_c} \left[ K_0(\phi_x + P\phi_k) - \frac{P\theta\varepsilon(e^{\theta\tau} - e^{-(\psi+\rho)\tau})}{\theta + \psi + \rho} + \frac{F\phi_x e^{-(\psi+\rho)\tau}}{\psi + \rho + g} \right]. \quad (6.34)$$

The superscript "I" stands for Type I regulation. The initial consumption rate depends positively on the initial stock of physical capital,  $K_0$ , the flow of aid promised to the country in the case of compliance,  $F$ , and the effectiveness of pollution control equipment,  $\phi_x$ . It depends negatively on the

imposed emissions threshold,  $\varepsilon$ , the compliance date,  $\tau$ , the intensity of emissions stemming from consumption process,  $\phi_c$ , the imposed rate of emissions decline,  $\theta$ , and finally on the price of pollution-control equipment,  $P$  (if  $\tau$  is sufficiently long or  $K_0$  sufficiently small). The detailed comparative statics are provided in the Appendix.

Knowing  $c_0^I$ , the present value of lifetime welfare can be obtained:

$$\begin{aligned}
W^I &= \int_0^\tau u(c_t, \varepsilon e^{\theta(\tau-t)}) e^{-\rho t} dt + \int_\tau^\infty u(\tilde{c}_t, \varepsilon) e^{-\rho t} dt \\
&= \int_0^\infty \ln(c_0^I e^{\psi t}) e^{-\rho t} dt - \int_0^\tau \frac{1}{2} (\varepsilon e^{\theta(\tau-t)})^2 e^{-\rho t} dt - \int_\tau^\infty \frac{1}{2} \varepsilon^2 e^{-\rho t} dt \\
&= \int_0^\infty \ln c_0^I e^{-\rho t} dt + \int_0^\infty \psi t e^{-\rho t} dt - \frac{1}{2} \varepsilon^2 \int_0^\tau e^{2\theta(\tau-t)-\rho t} dt - \frac{1}{2} \varepsilon^2 \int_\tau^\infty e^{-\rho t} dt \\
&= \frac{\ln c_0^I}{\rho} - \psi \left[ \frac{e^{-\rho t}}{\rho} \left( t + \frac{1}{\rho} \right) \right] \Big|_0^\infty - \frac{\varepsilon^2 e^{2\theta\tau}}{2} \int_0^\tau e^{-(2\theta+\rho)t} dt - \frac{\varepsilon^2}{2} \int_\tau^\infty e^{-\rho t} dt \\
&= \frac{\ln c_0^I}{\rho} + \frac{\psi}{\rho^2} - \frac{\varepsilon^2 (\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau})}{2\rho(2\theta + \rho)},
\end{aligned}$$

where the superscript "I" stands for "compliance with Type I regulation".

## Type II Regulation

Type II regulation states that the country must reduce its emissions to a given level  $\varepsilon$  by a given date  $\tau$ . The emissions reduction must follow a prespecified plan such that the rate of emissions decline must be equal to a given constant  $\theta$ . From time  $\tau$  onwards emissions must not exceed  $\varepsilon$ . If the economy complies with the regulation, it will start receiving a flow of aid (or monetary compensation) which is tied to the investment in pollution control  $F(\tilde{I}_t) > 0$  with  $F'(\tilde{I}_t) > 0$ . Thus the flow of aid is not declining over time, as in Type I regulation, but is conditional on abatement effort. This scheme is effectively identical to a subsidy on purchases of pollution-control equipment, although LDC becomes eligible for the subsidy only once it has complied with the regulation deadline.

The Hamiltonian associated with Phase II optimization program may be

written as:

$$H = u(\tilde{c}_t, \varepsilon) + \lambda_t [Q(K_t) - \tilde{c}_t - \tilde{I}_t P + F(\tilde{I}_t)] + \mu_t \tilde{I}_t + \eta_t [\phi_c \tilde{c}_t + \phi_k K_t - \phi_x X_t - \varepsilon].$$

The optimality conditions are (time subscripts are suppressed for notational convenience):

$$\tilde{c} : \quad \frac{\partial u}{\partial \tilde{c}} - \lambda + \eta \phi_c = 0, \quad (6.35)$$

$$\tilde{I} : \quad \lambda [F'(\tilde{I}) - P] + \mu = 0, \quad (6.36)$$

$$K : \quad \lambda Q'(K) + \eta \phi_k = \rho \lambda - \dot{\lambda}, \quad (6.37)$$

$$X : \quad -\eta \phi_x = \rho \mu - \dot{\mu}, \quad (6.38)$$

and the transversality condition  $\lim_{t \rightarrow \infty} K_t e^{-\rho t} = 0$ .

Assume, for simplicity, that  $F'(\tilde{I})$  is equal to a positive constant  $\sigma$ , i.e., the aid to LDC is proportional to its investment in pollution control. Then, from eq. (6.36), we have  $\mu = (P - \sigma)\lambda$  and thus  $\hat{\mu} = \hat{\lambda}$ . Dividing eq. (6.37) by  $\lambda$ , eq. (6.38) by  $\mu$ , and equating the resulting equations, we obtain  $\frac{\eta}{\lambda} = \frac{A(\sigma - P)}{\phi_x - \phi_k(\sigma - P)} \equiv \tilde{\gamma}$ . Using this in (6.37) yields a constant growth rate of  $\lambda$ , i.e.,  $\hat{\lambda} = \rho - A - \tilde{\gamma}\phi_k$ . Combining this with (6.35), we obtain the growth rate of consumption as

$$\hat{\tilde{c}} = \frac{A\phi_x}{\phi_k(P - \sigma) + \phi_x} - \rho \equiv \tilde{\psi} > \psi.$$

The last inequality holds because  $\psi = \frac{A\phi_x}{P\phi_k + \phi_x} - \rho$ . Therefore, under Type II regulation, when the aid is conditional on the investment in pollution control, the growth rate of consumption in the second phase (when the regulation is binding) is higher than under Type I regulation, where aid is unconditional.

Following similar steps as in the previous subsection, we have:

$$X_t = \frac{1}{\phi_x} \left[ \phi_k K_t + \phi_c \tilde{c}_\tau e^{\tilde{\psi}(t-\tau)} - \varepsilon \right]$$

and thus the investment rate in pollution control is given by

$$\tilde{I}_t = \dot{X}_t = \frac{1}{\phi_x} \left[ \phi_k \dot{K}_t + \tilde{\psi} \phi_c \tilde{c}_\tau e^{\tilde{\psi}(t-\tau)} \right].$$



Using this in (6.18) yields:

$$\dot{K}_t = (\tilde{\psi} + \rho)K_t - \tilde{\delta}_c \tilde{c}_\tau e^{\tilde{\psi}(t-\tau)},$$

where  $\tilde{\delta}_c = \frac{\phi_x + (P-\sigma)\phi_c \tilde{\psi}}{\phi_x + (P-\sigma)\phi_k}$ . Integrating the above differential equation from  $\tau$  to infinity and applying the transversality condition allows to solve for the initial consumption rate of Phase II:

$$\tilde{c}_\tau = \frac{\rho K_\tau}{\tilde{\delta}_c} = \frac{\rho K_\tau [\phi_x + (P-\sigma)\phi_k]}{\phi_x + (P-\sigma)\phi_c \tilde{\psi}}, \quad (6.39)$$

and  $K_\tau$  is the capital stock inherited from Phase I. Since the LDC's optimal program in Phase I under Type II regulation is identical to the one under Type I regulation, we already have the solution for  $K_\tau$  from the previous subsection. Evaluating eq. (6.33) at  $t = \tau$  and equating with  $K_\tau$  expressed in terms of  $\tilde{c}_\tau$  from eq. (6.39), we can solve for the initial consumption rate in Phase I:

$$c_0^{II} = \frac{\rho \left[ K_0 e^{\rho\tau} - \delta_\varepsilon \frac{e^{\rho\tau} - e^{-(\theta+\psi)\tau}}{\theta+\psi+\rho} \right]}{\frac{\phi_x + (P-\sigma)\phi_c \tilde{\psi}}{\phi_x + (P-\sigma)\phi_k} + \frac{(\phi_x + P\psi\phi_c)(e^{\rho\tau} - 1)}{\phi_x + P\phi_k}} \quad (6.40)$$

or, substituting for  $\delta_\varepsilon$ ,

$$c_0^{II} = \frac{\rho \left[ K_0 e^{\rho\tau} (\phi_x + P\phi_k) - \frac{(e^{\theta\tau} - e^{-(\rho+\psi)\tau}) P \theta \varepsilon e^{\rho\tau}}{(\theta+\psi+\rho)} \right] [\phi_x + (P-\sigma)\phi_k]}{\left[ \phi_x + (P-\sigma)\phi_c \tilde{\psi} \right] (\phi_x + P\phi_k) + [\phi_x + (P-\sigma)\phi_k] (\phi_x + P\psi\phi_c)(e^{\rho\tau} - 1)} \quad (6.41)$$

The present value of lifetime welfare under Type II regulation is given by:

$$W^{II} = \frac{\ln c_0^{II}}{\rho} + \frac{\psi + \tilde{\psi} e^{-\rho\tau}}{\rho^2} - \frac{\varepsilon^2 (\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau})}{2\rho(2\theta + \rho)}$$

Having solved for the lifetime welfare under the two regulation types, we are now in the position to analyze the conditions such that an LDC chooses to comply with the first or the second regulation or not to comply at all.

## 6.3 Analysis of Compliance

The country will chose to comply if and only if its lifetime welfare under compliance is at least as large as its welfare under non-compliance.

The policy tools at the disposal of the regulators (world community) are:

- emissions threshold  $\varepsilon$
- emissions decline rate  $\theta$
- compliance deadline  $\tau$
- pollution-control subsidy  $\sigma$
- compensation  $F$

The model also embeds the possibility of a technology transfer from the advanced to the developing countries by affecting  $\phi_c$ ,  $\phi_k$  and  $\phi_x$ .

What type of regulation the developing country is more likely to comply with?

Under what conditions?

Which tools are more effective in inducing compliance?

Do countries' characteristics (such as initial capital stocks, rate of time preference, polluting and abating intensities, etc.) matter for the compliance? If yes, then what type of regulation should be applied for what type of countries? (Given that less advanced countries are not homogeneous in terms of their development levels, it is natural to think that different types of regulations should be designed for different groups of countries...notion of differentiated responsibility)

### 6.3.1 Compliance with Type I Regulation vs Status Quo

This section examines the conditions that should be in place so that LDC complies voluntarily with the Type I regulation instead of choosing the status

quo (hereafter SQ). In particular, we look at the combinations of the emissions threshold  $\varepsilon$  and the rate of emissions decline,  $\theta$ , such that LDC is indifferent between the two options, i.e.,  $W^I = W$ . Let us define the difference between the two welfare levels as  $D^I \equiv W^I - W$ , so that

$$D^I = \frac{\ln c_0^I - \ln c_0}{\rho} - \frac{\varepsilon^2(\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau})}{2\rho(2\theta + \rho)} + \left( \frac{\gamma}{c_0(1 + \gamma\phi_c)} \right)^2 \frac{1}{2(\rho + 2\psi)}.$$

Setting  $D^I$  to zero defines a schedule in  $\varepsilon$  and  $\theta$  space along which LDC is indifferent between Type I regulation and SQ. The slope of the schedule is given by

$$\left. \frac{d\theta}{d\varepsilon} \right|_{D^I=0} = -\frac{\partial D^I / \partial \varepsilon}{\partial D^I / \partial \theta} = -\frac{\partial W^I / \partial \varepsilon}{\partial W^I / \partial \theta} < 0.$$

The numerator is unambiguously negative:

$$\frac{\partial W^I}{\partial \varepsilon} = \frac{1}{\rho c_0^I} \frac{\partial c_0^I}{\partial \varepsilon} - \varepsilon \frac{\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau}}{\rho(2\theta + \rho)} < 0,$$

where

$$\frac{\partial c_0^I}{\partial \varepsilon} = -\frac{\rho P \theta (e^{\theta\tau} - e^{-(\psi+\rho)\tau})}{(\phi_x + P\psi\phi_c)(\theta + \psi + \rho)} < 0 \quad \text{for } \tau > 0.$$

The denominator is also negative:

$$\frac{\partial W^I}{\partial \theta} = \frac{1}{\rho c_0^I} \frac{\partial c_0^I}{\partial \theta} - \frac{\varepsilon^2 [e^{2\theta\tau} [\tau(2\theta + \rho) - 1] + e^{-\rho\tau}]}{(2\theta + \rho)^2} < 0,$$

since

$$\frac{\partial c_0^I}{\partial \theta} = -\frac{\rho P \varepsilon [e^{\theta\tau} \tau \theta^2 + (\psi + \rho) [e^{\theta\tau} (1 + \tau\theta) - e^{-(\psi+\rho)\tau}]]}{(\phi_x + P\psi\phi_c)(\theta + \psi + \rho)^2} < 0$$

and

$$e^{2\theta\tau} [\tau(2\theta + \rho) - 1] + e^{-\rho\tau} > 0 \quad \text{for } \tau > 0.$$

Thus the  $D^I = 0$  schedule is negatively sloped: a smaller emissions target must be accompanied by a slower convergence rate in order to keep an LDC indifferent between complying with Type I regulation and Status Quo.

### 6.3.2 Compliance with Type II Regulation vs Status Quo

Similarly, define the difference between the welfare levels under Type II regulation and SQ as  $D^{II} \equiv W^{II} - W$ :

$$D^{II} = \frac{\ln c_0^{II} - \ln c_0}{\rho} + \frac{\tilde{\psi}e^{-\rho\tau}}{\rho^2} - \frac{\varepsilon^2(\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau})}{2\rho(2\theta + \rho)} + \left( \frac{\gamma}{c_0(1 + \gamma\phi_c)} \right)^2 \frac{1}{2(\rho + 2\psi)}.$$

The slope of the  $D^{II} = 0$  schedule is given by

$$\left. \frac{d\theta}{d\varepsilon} \right|_{D^{II}=0} = - \frac{\partial D^{II} / \partial \varepsilon}{\partial D^{II} / \partial \theta} = - \frac{\partial W^{II} / \partial \varepsilon}{\partial W^{II} / \partial \theta} < 0.$$

The numerator is unambiguously negative:

$$\frac{\partial W^{II}}{\partial \varepsilon} = \frac{1}{\rho c_0^{II}} \frac{\partial c_0^{II}}{\partial \varepsilon} - \varepsilon \frac{\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau}}{\rho(2\theta + \rho)} < 0,$$

where

$$\frac{\partial c_0^{II}}{\partial \varepsilon} = - \frac{\frac{(e^{\theta\tau} - e^{-(\rho+\psi)\tau})P\theta\rho e^{\rho\tau}}{(\theta+\psi+\rho)} [\phi_x + (P - \sigma)\phi_k]}{[\phi_x + (P - \sigma)\phi_c\tilde{\psi}](\phi_x + P\phi_k) + [\phi_x + (P - \sigma)\phi_k](\phi_x + P\psi\phi_c)(e^{\rho\tau} - 1)} < 0.$$

We can also write

$$\frac{\partial c_0^{II}}{\partial \varepsilon} = \frac{\partial c_0^I}{\partial \varepsilon} \mu,$$

where

$$\mu \equiv \frac{e^{\rho\tau}(\phi_x + P\psi\phi_c)[\phi_x + (P - \sigma)\phi_k]}{[\phi_x + (P - \sigma)\phi_c\tilde{\psi}](\phi_x + P\phi_k) + [\phi_x + (P - \sigma)\phi_k](\phi_x + P\psi\phi_c)(e^{\rho\tau} - 1)} > 0.$$

The denominator is also negative:

$$\frac{\partial W^{II}}{\partial \theta} = \frac{1}{\rho c_0^{II}} \frac{\partial c_0^{II}}{\partial \theta} - \frac{\varepsilon^2 [e^{2\theta\tau}[\tau(2\theta + \rho) - 1] + e^{-\rho\tau}]}{(2\theta + \rho)^2} < 0,$$

since

$$\frac{\partial c_0^{II}}{\partial \theta} = - \frac{\frac{\rho P \varepsilon \left[ \phi_x + (P - \sigma)\phi_k \right] \left\{ e^{(\theta+\rho)\tau}[(\psi+\rho)(1+\tau\theta) + \tau\theta^2] - e^{-\psi\tau}(\psi+\rho) \right\}}{(\theta+\psi+\rho)^2}}{[\phi_x + (P - \sigma)\phi_c\tilde{\psi}](\phi_x + P\phi_k) + [\phi_x + (P - \sigma)\phi_k](\phi_x + P\psi\phi_c)(e^{\rho\tau} - 1)} =$$

$$= \frac{\partial c_0^I}{\partial \theta} \mu < 0.$$

Thus the  $D^{II} = 0$  schedule is negatively sloped: a stricter emissions target must be accompanied by a slower convergence rate in order to keep an LDC indifferent between complying with Type II regulation and Status Quo. It can be shown that the  $D^{II} = 0$  schedule is flatter than the  $D^I = 0$  schedule (see Appendix).

### 6.3.3 Compliance with Type I vs Type II Regulation

Under what conditions an LDC is more likely to comply with one or the other type of regulation? The answer to this question depends on how the LDC's welfare is affected by various policies under the two regulations. Let us define the difference in lifetime welfare under regulation II ( $W^{II}$ ) and regulation I ( $W^I$ ) by  $D$ , i.e.,

$$D \equiv W^{II} - W^I = \frac{\ln c_0^{II} - \ln c_0^I}{\rho} + \frac{\tilde{\psi} e^{-\rho\tau}}{\rho^2}.$$

Clearly, when  $c_0^{II} > c_0^I$ , the difference in welfare is positive, so that an LDC will always choose to comply with Type II regulation but not with Type I. For the rest of the analysis we continue to assume that the initial conditions are such that  $c_0^{II} < c_0^I$ . We are interested in combinations of  $\theta$  and  $\varepsilon$  such that  $D = 0$ . The slope of the  $D = 0$  schedule is given by

$$\begin{aligned} \left. \frac{d\theta}{d\varepsilon} \right|_{D=0} &= -\frac{\partial D / \partial \varepsilon}{\partial D / \partial \theta} = -\frac{\partial W^{II} / \partial \varepsilon - \partial W^I / \partial \varepsilon}{\partial W^{II} / \partial \theta - \partial W^I / \partial \theta} = \\ &= -\frac{\frac{1}{c_0^{II}} \frac{\partial c_0^{II}}{\partial \varepsilon} - \frac{1}{c_0^I} \frac{\partial c_0^I}{\partial \varepsilon}}{\frac{1}{c_0^{II}} \frac{\partial c_0^{II}}{\partial \theta} - \frac{1}{c_0^I} \frac{\partial c_0^I}{\partial \theta}} = -\frac{\frac{\partial c_0^I}{\partial \varepsilon} \left( \frac{1}{c_0^{II}} \mu - \frac{1}{c_0^I} \right)}{\frac{\partial c_0^I}{\partial \theta} \left( \frac{1}{c_0^{II}} \mu - \frac{1}{c_0^I} \right)} = -\frac{\frac{\partial c_0^I}{\partial \varepsilon}}{\frac{\partial c_0^I}{\partial \theta}} < 0. \end{aligned}$$

It can be shown the  $D = 0$  schedule is flatter than the  $D^{II} = 0$  schedule (see Appendix).

The relative positions of the three schedules are illustrated graphically in figure 6.1. The schedules divide the quadrant into six zones. Each zone

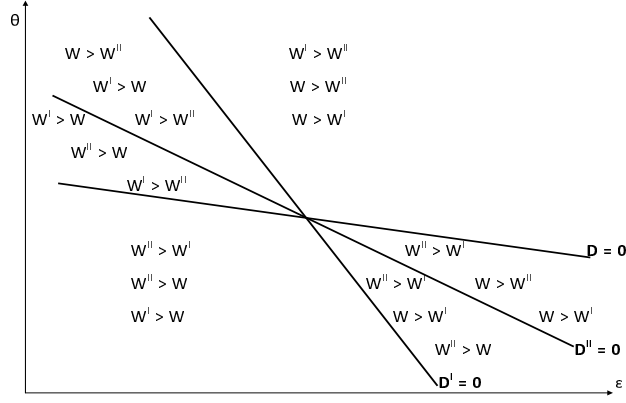


Figure 6.1: Emissions threshold and emissions reduction speed.

is characterized by the combinations of  $\theta$  and  $\varepsilon$  such that one of the three options, i.e., the Status Quo or Type I regulation or Type II regulation, dominates the other two. An increase in  $\varepsilon$  has a negative effect on  $W^I$  and  $W^{II}$  and no effect on the status quo welfare. Thus,  $W > W^I$  to the right of  $D^I = 0$  and  $W > W^{II}$  to the right of  $D^{II} = 0$ . We also know that an increase in  $\varepsilon$  has a more negative effect on  $W^{II}$  than on  $W^I$  and hence  $W^I > W^{II}$  above and to the right of  $D = 0$ . Thus the six zones can be grouped in three: (i) the zone of compliance with Type I regulation (hereafter  $ZC^I$ ), (ii) the zone of compliance with Type II regulation (hereafter  $ZC^{II}$ ), and (iii) the zone of non-compliance (hereafter  $ZNC$ ), as illustrated in figure 6.2a. Type I regulation is preferred when the emissions target,  $\varepsilon$ , is relatively low while the convergence rate,  $\theta$ , is moderate. Type II regulation is preferred for a wide range of emissions threshold but with the convergence rate being faster (slower) the higher (lower) the threshold. The non-compliance is preferred when either the convergence rate is relatively high and the emissions target relatively low or when both are relatively high. This latter case arises when the emissions target imposed by a regulation is in fact above the emissions level attained by a non-regulated economy. This situation is not relevant for

our further analysis.

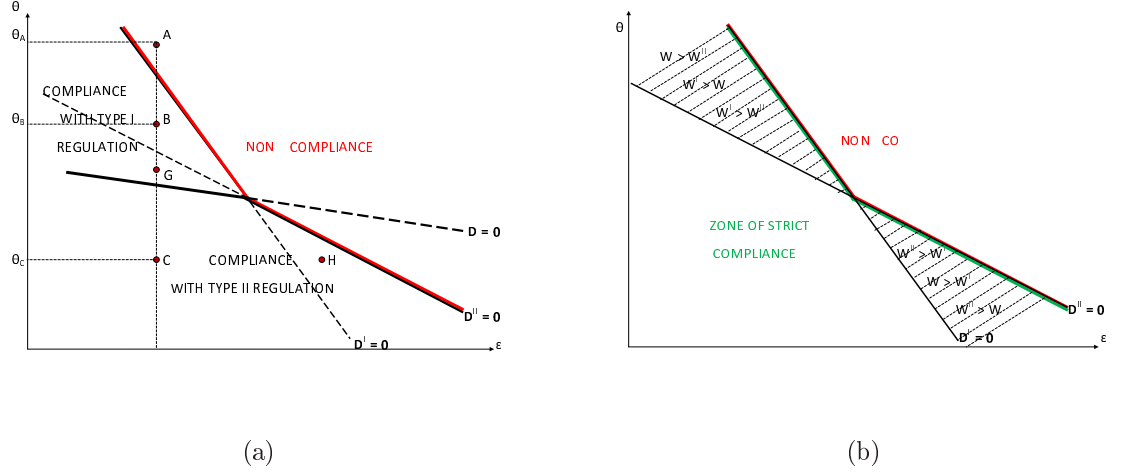


Figure 6.2: Zones of compliance and non-compliance.

Consider, for instance, points like A, B, and C in figure 6.2a, which are all located at the same targeted emissions level. Depending on the proposed convergence rate, an LDC will either choose not to comply with any regulation (if  $\theta$  is relatively high, such as  $\theta_A$ ), or to comply with Type I regulation (if  $\theta$  is relatively moderate, such as  $\theta_B$ ), or to comply with Type II regulation (if  $\theta$  is relatively low, such as  $\theta_C$ ). Voluntary compliance with Type II regulation requires a slower convergence rate,  $\theta$ , because the (negative) effect of  $\theta$  on  $W^{II}$  (working through the consumption rate) is stronger than on  $W^I$ . Thus, for any targeted emissions threshold, the choice of the convergence speed determines which regulation type will be voluntarily accepted by an LDC.

Consider next a point in the zone of compliance with Type I regulation such as G. Assume that the combination of  $\theta$  and  $\varepsilon$  corresponding to point G (which lies in  $ZC^I$ ) is proposed within the Type II regulation but Type I is *not* offered. Will an LDC still comply? The answer is yes, because for this combination of  $\theta$  and  $\varepsilon$ ,  $W^{II}$  exceeds  $W$ , as can be seen in figure 6.1. If, however, the combination B is proposed, then an LDC will choose not to comply since  $W^{II}$  falls short of  $W$  for the corresponding  $\theta$  and  $\varepsilon$  (see figure 6.1). More generally, for any combination of  $\theta$  and  $\varepsilon$  which lies between

$D^I = 0$  and  $D^{II} = 0$  to the left of their intersection, an LDC will prefer non-compliance if only Type II regulation is offered. Similarly, for any combination of  $\theta$  and  $\varepsilon$  which lies between  $D^I = 0$  and  $D^{II} = 0$  to the right of their intersection (such as, e.g., point H), an LDC will choose not to comply if Type I is the only regulation available. If, however,  $\theta$  and  $\varepsilon$  lie between  $D = 0$  and  $D^{II} = 0$  to the left of their intersection, belonging to  $ZC^I$ , but only Type II regulation is offered, then an LDC will still choose to comply. And finally, for any combinations of  $\theta$  and  $\varepsilon$  which fall below  $D = 0$  and to the left of  $D^I = 0$  an LDC will voluntarily comply, regardless of whether the regulation is of Type I or Type II. This zone will be referred to as Zone of Strict Compliance (see figure 6.2b).

## 6.4 Policy Analysis

### 6.4.1 Unconditional Aid, $F$

In the present framework, the unconditional foreign aid, or a monetary compensation, is the amount  $F$  given to LDC on date  $\tau$  if compliance with Type I regulation is achieved. During the subsequent periods, i.e.,  $t > \tau$ , LDC receives  $F e^{-g(t-\tau)}$ , where  $g$  is the rate at which the foreign aid declines over time. As mentioned earlier, this decline in the amount of monetary transfer may reflect the limited commitment on behalf of donors or gradual improvement in the standard of living in LDC due to development process. The unconditional aid,  $F$ , affects only the lifetime welfare  $W^I$  and has no effect on either  $W^{II}$  or  $W$ . A higher  $F$  unambiguously improves  $W^I$  through its positive effect on the initial consumption rate  $c_0^I$ :

$$\frac{\partial c_0^I}{\partial F} = \frac{\rho \phi_x e^{-(\psi+\rho)\tau}}{(\phi_x + P\psi\phi_c)(\psi + \rho + g)} > 0.$$

This induces a rightward shift of the  $D^I = 0$  schedule and a downward shift of the  $D = 0$  schedule (see figure 6.3). The magnitudes of the respective



(horizontal) shifts are given by

$$\left. \frac{d\varepsilon}{dF} \right|_{D^I=0} = - \frac{\frac{1}{c_0^I} \frac{\partial c_0^I}{\partial F}}{\frac{1}{c_0^I} \frac{\partial c_0^I}{\partial \varepsilon} - \frac{\varepsilon(\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau})}{2\theta + \rho}} > 0$$

and

$$\left. \frac{d\varepsilon}{dF} \right|_{D=0} = - \frac{-\frac{1}{c_0^I} \frac{\partial c_0^I}{\partial F}}{\frac{1}{c_0^{II}} \frac{\partial c_0^{II}}{\partial \varepsilon} - \frac{1}{c_0^I} \frac{\partial c_0^I}{\partial \varepsilon}} < 0.$$

The dashed lines in figure 6.3 represent the original equilibrium, while the

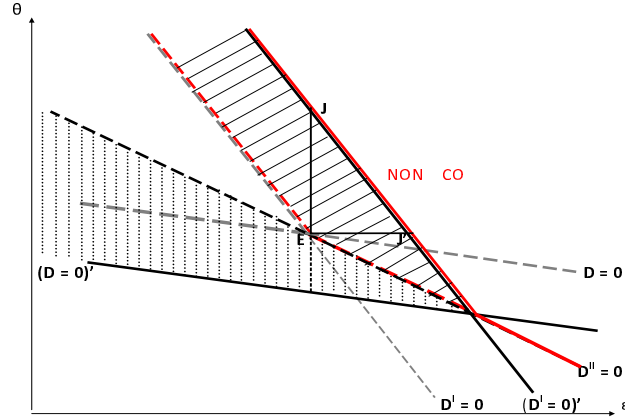


Figure 6.3: Increase in foreign aid.

solid lines labeled  $(D^I = 0)'$  and  $(D = 0)'$  are drawn for a higher value of  $F$ . The overall effect of the policy is to expand the zone of compliance with Type I regulation ( $ZC^I$ ) at the expense of the zone of strict non-compliance ( $ZNC$ ), shaded by the slanted solid lines, and the zone of compliance with Type II regulation ( $ZC^{II}$ ), shaded by the vertical dotted lines. When a higher amount of foreign aid is promised in case of compliance with Type I regulation, an LDC is willing to accept a wider range of convergence rates and emission thresholds. These include faster convergence rates for the same emissions-target level, as in the area between  $D^I = 0$  and  $(D^I = 0)'$  to the left

of  $EJ$  line, but also faster convergence rates accompanied by a less stringent emissions target, as in the area  $EJ'J$ .

#### 6.4.2 Pollution-Control Subsidy, $\sigma$

The pollution-control subsidy,  $\sigma$ , affects only  $W^{II}$  and hence induces shifts of  $D^{II} = 0$  and  $D = 0$ , while  $D^I = 0$  schedule is not affected. The horizontal shift of  $D^{II} = 0$  is given by:

$$\left. \frac{d\varepsilon}{d\sigma} \right|_{D^{II}=0} = - \frac{\frac{1}{c_0^{II}} \frac{\partial c_0^{II}}{\partial \sigma} + \frac{e^{-\rho\tau}}{\rho} \frac{\partial \tilde{\psi}}{\partial \sigma}}{\frac{1}{c_0^{II}} \frac{\partial c_0^{II}}{\partial \varepsilon} - \frac{\varepsilon(\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau})}{2\theta + \rho}},$$

where the denominator is unambiguously negative (as has been shown earlier), while the numerator is positive:

$$\begin{aligned} & \frac{1}{c_0^{II}} \frac{\partial c_0^{II}}{\partial \sigma} + \frac{e^{-\rho\tau}}{\rho} \frac{\partial \tilde{\psi}}{\partial \sigma} = \\ &= \frac{\frac{\phi_x + (P-\sigma)\phi_c \tilde{\psi}}{\phi_x + (P-\sigma)\phi_k} (\phi_x + P\phi_k) + (\phi_x + P\psi\phi_c)(e^{\rho\tau} - 1)}{\rho \left[ K_0 e^{\rho\tau} (\phi_x + P\phi_k) - \frac{(e^{\theta\tau} - e^{-(\rho+\psi)\tau}) P \theta \varepsilon e^{\rho\tau}}{(\theta + \psi + \rho)} \right]} \times \\ & \times \frac{-\rho \left[ K_0 e^{\rho\tau} (\phi_x + P\phi_k) - \frac{(e^{\theta\tau} - e^{-(\rho+\psi)\tau}) P \theta \varepsilon e^{\rho\tau}}{(\theta + \psi + \rho)} \right] (\phi_x + P\phi_k)}{\left\{ \frac{\phi_x + (P-\sigma)\phi_c \tilde{\psi}}{\phi_x + (P-\sigma)\phi_k} (\phi_x + P\phi_k) + (\phi_x + P\psi\phi_c)(e^{\rho\tau} - 1) \right\}^2} \times \\ & \times \frac{\partial}{\partial \sigma} \left[ \frac{\phi_x + (P-\sigma)\phi_c \tilde{\psi}}{\phi_x + (P-\sigma)\phi_k} \right] + \frac{e^{-\rho\tau}}{\rho} \frac{\partial \tilde{\psi}}{\partial \sigma} = \\ &= - \frac{(\phi_x + P\phi_k) \frac{\partial}{\partial \sigma} \left[ \frac{\phi_x + (P-\sigma)\phi_c \tilde{\psi}}{\phi_x + (P-\sigma)\phi_k} \right]}{\frac{\phi_x + (P-\sigma)\phi_c \tilde{\psi}}{\phi_x + (P-\sigma)\phi_k} (\phi_x + P\phi_k) + (\phi_x + P\psi\phi_c)(e^{\rho\tau} - 1)} + \frac{e^{-\rho\tau}}{\rho} \frac{A\phi_x \phi_k}{[\phi_x + (P-\sigma)\phi_k]^2} = \\ &= \frac{A\phi_x \phi_k e^{-\rho\tau}}{\rho [\phi_x + (P-\sigma)\phi_k]^2} + \\ &+ \frac{A\phi_x^2 (\phi_x + P\phi_k)}{[\phi_x + (P-\sigma)\phi_k]^2 \left\{ \frac{\phi_x + (P-\sigma)\phi_c \tilde{\psi}}{\phi_x + (P-\sigma)\phi_k} (\phi_x + P\phi_k) + (\phi_x + P\psi\phi_c)(e^{\rho\tau} - 1) \right\}^2} - \\ &- \frac{\rho(\phi_x + P\phi_k)}{\left\{ \frac{\phi_x + (P-\sigma)\phi_c \tilde{\psi}}{\phi_x + (P-\sigma)\phi_k} (\phi_x + P\phi_k) + (\phi_x + P\psi\phi_c)(e^{\rho\tau} - 1) \right\}^2} > 0. \end{aligned}$$

Thus, the  $D^{II} = 0$  schedule shifts to the right when  $\sigma$  increases.

The horizontal shift of  $D = 0$  schedule is given by:

$$\left. \frac{d\varepsilon}{d\sigma} \right|_{D^{II}=0} = - \frac{\frac{1}{c_0^{II}} \frac{\partial c_0^{II}}{\partial \sigma} + \frac{e^{-\rho\tau}}{\rho} \frac{\partial \tilde{\psi}}{\partial \sigma}}{\frac{1}{c_0^{II}} \frac{\partial c_0^{II}}{\partial \varepsilon} - \frac{1}{c_0^I} \frac{\partial c_0^I}{\partial \varepsilon}} > 0,$$

since the numerator is positive (as just proved) and the denominator is negative (see Appendix). Thus, the  $D = 0$  schedule shifts up and to the right when  $\sigma$  increases. This is illustrated graphically in figure 6.4. The total effect of the policy (i.e., an increase in the pollution-control subsidy) is to expand the zone of compliance with Type II regulation at the expense of  $ZC^I$  (shaded by dotted vertical lines) and  $ZNC$  (shaded by solid slanted lines). Consequently both  $ZC^I$  and  $ZNC$  shrink. With a higher  $\sigma$ , an LDC is willing to comply with the Type II regulation characterized by faster convergence rates for any given emissions target.

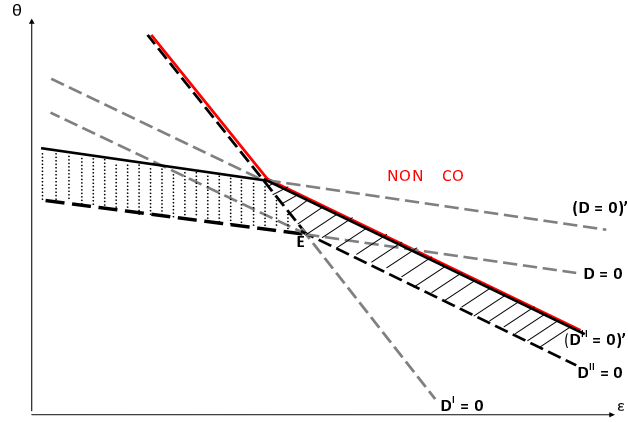


Figure 6.4: Increase in pollution-control subsidy.

## 6.5 Conclusion

There is a global agreement that efforts should be made to deal with climate change. However, there is not yet an agreement on how these efforts should

be shared between advanced and developing countries. Advanced economies fear the loss of competitiveness of their domestic firms when the latter must purchase pollution permits in order to comply with environmental standards. Developing countries prioritize economic growth and improvement in the standard of living over environmental problems. This paper looks at the problem of compliance with environmental regulation from the perspective of a developing country and examines the constellations of conditions/policies that should be in place in order to guarantee voluntary compliance.

I focus on supporting/stimulating measures provided by the advanced countries to the developing country, such as monetary transfers. More specifically, I analyze two types of regulation: One where a predefined transfer is initiated on the date of compliance with emissions target; and the other where the amount transferred is tied to emissions-control effort. Both regulations, however, impose an emissions target that should be achieved by a given date and the rate of convergence to this target. I show the combinations of the emissions target and the convergence rate such that the country is willing to comply with either the first or the second regulation type or does not comply at all. The main result of the paper is that offering one or the other option is inefficient. The chances that an LDC complies voluntarily with environmental standards are higher when a menu of options is on the table. The direct implication of this results is that the number and/or diversity of countries willing to comply with environmental standards is also higher when a variety of alternatives is available instead of just one regulation type.

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## 6.6 Appendix: Comparisons of Slopes

### 6.6.1 Slopes of $D^I = 0$ and $D^{II} = 0$ Schedules

By comparing the absolute values of the slopes, we need to prove that

$$\begin{aligned} \left| \frac{d\theta}{d\varepsilon} \right|_{D^{II}=0} &< \left| \frac{d\theta}{d\varepsilon} \right|_{D^I=0} \\ \frac{\partial W^{II}/\partial \varepsilon}{\partial W^{II}/\partial \theta} &< \frac{\partial W^I/\partial \varepsilon}{\partial W^I/\partial \theta} \\ \frac{\frac{1}{\rho c_0^{II}} \frac{\partial c_0^{II}}{\partial \varepsilon} - \varepsilon \frac{\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau}}{\rho(2\theta+\rho)}}{\frac{1}{\rho c_0^{II}} \frac{\partial c_0^{II}}{\partial \theta} - \frac{\varepsilon^2 [e^{2\theta\tau} [\tau(2\theta+\rho)-1] + e^{-\rho\tau}]}{(2\theta+\rho)^2}} &< \frac{\frac{1}{\rho c_0^I} \frac{\partial c_0^I}{\partial \varepsilon} - \varepsilon \frac{\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau}}{\rho(2\theta+\rho)}}{\frac{1}{\rho c_0^I} \frac{\partial c_0^I}{\partial \theta} - \frac{\varepsilon^2 [e^{2\theta\tau} [\tau(2\theta+\rho)-1] + e^{-\rho\tau}]}{(2\theta+\rho)^2}} \end{aligned}$$

For notational convenience define  $y \equiv \varepsilon \frac{\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau}}{\rho(2\theta+\rho)}$  and  $z \equiv \frac{\varepsilon^2 [e^{2\theta\tau} [\tau(2\theta+\rho)-1] + e^{-\rho\tau}]}{(2\theta+\rho)^2}$ .

Then we can rewrite the inequality as:

$$\begin{aligned} \frac{\frac{1}{\rho c_0^{II}} \frac{\partial c_0^{II}}{\partial \varepsilon} - y}{\frac{1}{\rho c_0^{II}} \frac{\partial c_0^{II}}{\partial \theta} - z} &< \frac{\frac{1}{\rho c_0^I} \frac{\partial c_0^I}{\partial \varepsilon} - y}{\frac{1}{\rho c_0^I} \frac{\partial c_0^I}{\partial \theta} - z} \\ \left( \frac{1}{\rho c_0^{II}} \frac{\partial c_0^{II}}{\partial \varepsilon} - y \right) \left( \frac{1}{\rho c_0^I} \frac{\partial c_0^I}{\partial \theta} - z \right) &< \left( \frac{1}{\rho c_0^{II}} \frac{\partial c_0^{II}}{\partial \theta} - z \right) \left( \frac{1}{\rho c_0^I} \frac{\partial c_0^I}{\partial \varepsilon} - y \right) \end{aligned}$$

multiplying the terms and recalling that  $\frac{\partial c_0^{II}}{\partial \varepsilon} = \frac{\partial c_0^I}{\partial \varepsilon} \mu$  and  $\frac{\partial c_0^{II}}{\partial \theta} = \frac{\partial c_0^I}{\partial \theta} \mu$  we obtain

$$\begin{aligned} \frac{1}{\rho c_0^{II}} \frac{\partial c_0^I}{\partial \varepsilon} \mu \frac{1}{\rho c_0^I} \frac{\partial c_0^I}{\partial \theta} - z \frac{1}{\rho c_0^{II}} \frac{\partial c_0^I}{\partial \varepsilon} \mu - y \frac{1}{\rho c_0^I} \frac{\partial c_0^I}{\partial \theta} + yz &< \\ &< \frac{1}{\rho c_0^{II}} \frac{\partial c_0^I}{\partial \theta} \mu \frac{1}{\rho c_0^I} \frac{\partial c_0^I}{\partial \varepsilon} - y \frac{1}{\rho c_0^{II}} \frac{\partial c_0^I}{\partial \theta} \mu - z \frac{1}{\rho c_0^I} \frac{\partial c_0^I}{\partial \varepsilon} + yz. \end{aligned}$$

Eliminating identical terms on both sides and multiplying by  $\rho$  we are left with

$$z \frac{\partial c_0^I}{\partial \varepsilon} \left( \frac{1}{c_0^I} - \frac{1}{c_0^{II}} \mu \right) < y \frac{\partial c_0^I}{\partial \theta} \left( \frac{1}{c_0^I} - \frac{1}{c_0^{II}} \mu \right).$$

Given that the term in the parentheses on the LHS is identical to the one on the RHS, we can divide through. However we need to keep in mind that

this term is negative, so that division entails a change of the inequality sign.

Then we have

$$\begin{aligned}
&\Rightarrow z \frac{\partial c_0^I}{\partial \varepsilon} > y \frac{\partial c_0^I}{\partial \theta} \\
&\Rightarrow -\frac{\varepsilon^2 [e^{2\theta\tau}[\tau(2\theta + \rho) - 1] + e^{-\rho\tau}]}{(2\theta + \rho)^2} \frac{\rho P \theta (e^{\theta\tau} - e^{-(\psi+\rho)\tau})}{(\phi_x + P\psi\phi_c)(\theta + \psi + \rho)} > \\
&> -\frac{\rho P \varepsilon [e^{\theta\tau}\tau\theta^2 + (\psi + \rho)[e^{\theta\tau}(1 + \tau\theta) - e^{-(\psi+\rho)\tau}]]}{(\phi_x + P\psi\phi_c)(\theta + \psi + \rho)^2} \varepsilon \frac{\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau}}{\rho(2\theta + \rho)} \\
&\Rightarrow -\frac{[e^{2\theta\tau}[\tau(2\theta + \rho) - 1] + e^{-\rho\tau}] \theta (e^{\theta\tau} - e^{-(\psi+\rho)\tau})}{2\theta + \rho} > \\
&> -\frac{(\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau}) [e^{\theta\tau}[\tau\theta^2 + (\psi + \rho)(1 + \tau\theta)] - (\psi + \rho)e^{-(\psi+\rho)\tau}]}{\rho(\theta + \psi + \rho)}
\end{aligned}$$

Multiplying both sides by  $-(2\theta + \rho)\rho(\theta + \psi + \rho) < 0$  and noting that again the inequality will change sign, we get

$$\begin{aligned}
&\Rightarrow \rho(\theta + \psi + \rho) [e^{2\theta\tau}[\tau(2\theta + \rho) - 1] + e^{-\rho\tau}] \theta (e^{\theta\tau} - e^{-(\psi+\rho)\tau}) < \\
&< (2\theta + \rho) (\rho e^{2\theta\tau} + 2\theta e^{-\rho\tau}) [e^{\theta\tau}[\tau\theta^2 + (\psi + \rho)(1 + \tau\theta)] - (\psi + \rho)e^{-(\psi+\rho)\tau}] \\
&\Rightarrow e^{2\theta\tau} \{ \rho(\theta + \psi + \rho)[\tau(2\theta + \rho) - 1]\theta (e^{\theta\tau} - e^{-(\psi+\rho)\tau}) \} + \\
&+ e^{-\rho\tau} \{ \rho(\theta + \psi + \rho)\theta (e^{\theta\tau} - e^{-(\psi+\rho)\tau}) \} < \\
&< e^{2\theta\tau} (2\theta + \rho) \rho [e^{\theta\tau}[\tau\theta^2 + (\psi + \rho)(1 + \tau\theta)] - (\psi + \rho)e^{-(\psi+\rho)\tau}] + \\
&+ e^{-\rho\tau} (2\theta + \rho) 2\theta [e^{\theta\tau}[\tau\theta^2 + (\psi + \rho)(1 + \tau\theta)] - (\psi + \rho)e^{-(\psi+\rho)\tau}]
\end{aligned}$$

Now compare the terms multiplying  $e^{2\theta\tau}$  on the LHS and the RHS:

$$\begin{aligned}
&\Rightarrow \rho(\theta + \psi + \rho)[\tau(2\theta + \rho) - 1]\theta (e^{\theta\tau} - e^{-(\psi+\rho)\tau}) \sim \\
&\sim (2\theta + \rho)\rho [e^{\theta\tau}[\tau\theta^2 + (\psi + \rho)(1 + \tau\theta)] - (\psi + \rho)e^{-(\psi+\rho)\tau}] \quad \Bigg| \div \rho \\
&\Rightarrow e^{\theta\tau} \{ (\theta + \psi + \rho)[\tau(2\theta + \rho) - 1]\theta - (2\theta + \rho)[\tau\theta^2 + (\psi + \rho)(1 + \tau\theta)] \} \sim \\
&\sim e^{-(\psi+\rho)} \{ (\theta + \psi + \rho)[\tau(2\theta + \rho) - 1]\theta - (2\theta + \rho)(\psi + \rho) \}
\end{aligned}$$

Define the term on the LHS as a function  $\alpha(\tau)$  and the term on the RHS as a function  $\beta(\tau)$ . At  $\tau = 0$  we have  $\alpha(0) = \beta(0) = -\theta(\theta + \psi + \rho) - (2\theta + \rho)(\psi + \rho)$ .

The slopes are given by  $\frac{d\alpha}{d\tau} = -[\theta(\theta + \psi + \rho) - (2\theta + \rho)(\psi + \rho)]\theta e^{\theta\tau} < 0$  and  $\frac{d\beta}{d\tau} = \{ -(\psi + \rho) [(\theta + \psi + \rho)[\tau(2\theta + \rho) - 1]\theta - (2\theta + \rho)(\psi + \rho)] + \theta(\theta + \psi + \rho)(2\theta + \rho) \} \times$



$e^{-(\psi+\rho)\tau} \geq 0$ . It can be shown that  $\beta(\tau)$  is monotonically rising on  $\tau \in [0, \tau^*)$ , where  $\tau^* = \frac{\theta(\theta+\psi+\rho)(2\theta+\rho)+(\psi+\rho)[(2\theta+\rho)(\psi+\rho)+\theta(\theta+\psi+\rho)]}{\theta(\theta+\psi+\rho)(2\theta+\rho)(\psi+\rho)} > 0$  is the maximum, and monotonically declining on  $\tau \in (\tau^*, \infty)$ . There is a unique  $\bar{\tau} = \frac{\theta(\theta+\psi+\rho)+(2\theta+\rho)(\psi+\rho)}{\theta(\theta+\psi+\rho)(2\theta+\rho)} < \tau^*$  such that  $\beta(\bar{\tau}) = 0$ , a unique inflection point  $\tilde{\tau} = \frac{2\theta(\theta+\psi+\rho)(2\theta+\rho)+(\psi+\rho)[(2\theta+\rho)(\psi+\rho)+\theta(\theta+\psi+\rho)]}{\theta(\theta+\psi+\rho)(2\theta+\rho)(\psi+\rho)} > \tau^*$ , and  $\lim_{\tau \rightarrow \infty} \beta(\tau) = 0$ . Given these characteristics, it is clear that  $\alpha(\tau) < \beta(\tau) \forall \tau > 0$ . A similar analysis can be done for the terms multiplying  $e^{-\rho\tau}$  to show that the term on the LHS is smaller than on the RHS. Thus we proved that the slope of  $D^{II} = 0$  is smaller in absolute value than the slope of  $D^I = 0$ .

### Slopes of $D = 0$ and $D^{II} = 0$ Schedules

It can be shown the  $D = 0$  schedule is flatter than the  $D^{II} = 0$  schedule:

$$\begin{aligned}
\left| \frac{d\theta}{d\varepsilon} \right|_{D^{II}=0} &> \left| \frac{d\theta}{d\varepsilon} \right|_{D=0} \\
\frac{\frac{1}{\rho c_0^{II}} \frac{\partial c_0^{II}}{\partial \varepsilon} - y}{\frac{1}{\rho c_0^{II}} \frac{\partial c_0^{II}}{\partial \theta} - z} &> \frac{\frac{\partial c_0^I}{\partial \varepsilon}}{\frac{\partial c_0^I}{\partial \theta}} \\
\frac{\frac{1}{\rho c_0^{II}} \frac{\partial c_0^I}{\partial \varepsilon} \mu - y}{\frac{1}{\rho c_0^{II}} \frac{\partial c_0^I}{\partial \theta} \mu - z} &> \frac{\frac{\partial c_0^I}{\partial \varepsilon}}{\frac{\partial c_0^I}{\partial \theta}} \\
\left( \frac{1}{\rho c_0^{II}} \frac{\partial c_0^I}{\partial \varepsilon} \mu - y \right) \frac{\partial c_0^I}{\partial \theta} &> \left( \frac{1}{\rho c_0^{II}} \frac{\partial c_0^I}{\partial \theta} \mu - z \right) \frac{\partial c_0^I}{\partial \varepsilon} \\
\frac{1}{\rho c_0^{II}} \frac{\partial c_0^I}{\partial \varepsilon} \mu \frac{\partial c_0^I}{\partial \theta} - y \frac{\partial c_0^I}{\partial \theta} &> \frac{1}{\rho c_0^{II}} \frac{\partial c_0^I}{\partial \theta} \mu \frac{\partial c_0^I}{\partial \varepsilon} - z \frac{\partial c_0^I}{\partial \varepsilon} \\
-y \frac{\partial c_0^I}{\partial \theta} &> -z \frac{\partial c_0^I}{\partial \varepsilon} \\
y \frac{\partial c_0^I}{\partial \theta} &< z \frac{\partial c_0^I}{\partial \varepsilon}
\end{aligned}$$

We have proved in the previous subsection that the above inequality holds true for any  $\tau > 0$ . Thus the slope of  $D^{II} = 0$  is larger in absolute value than the slope of  $D = 0$ .

# Curriculum Vitae

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