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Suayp Mehmet Eruzun

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Abstract

Motivated by an observed gap in the current economic literature, this thesis presents a theoretical framework examining environmental migration from the global south to the north, interlinked with the paradigms of climate finance and the success probability of migration in the face of border enforcement of Host country. Influenced by Brausmann and Ddjajić's (2022) study on migration dynamics, this research employs three models. The first model describes the benefits host nations gain by prioritizing environmental abatement over border controls, resulting in reduced migrant influx and enforcement costs, benefitting both Source and Host countries. The next analysis introduces budgetary constraints, highlighting the balance nations must strike between environmental abatement and border control expenditures. Emphasizing that mitigation in the Source country might cut border expenses and migrant numbers, while the study questions its effectiveness. The final model dives into the balance between migration decisions and abatement efforts. Key insights suggest that the stability of migration dynamics relies on specific economic parameters, like the country's future discount rate and the inflow rate of the stock. Moreover, abatement measures can notably alter the probability of successful migration and overall stock of migrants, dependent on varying climate finance levels. In conclusion, this work synthesizes theoretical insights with the real-world challenges of climate-driven migration, advocating an integrated combination of policy, finance, and migration in the face of global climate change.

Zusammenfassung

Angeregt durch eine festgestellte Lücke in der aktuellen wirtschaftlichen Literatur präsentiert diese Arbeit einen theoretischen Rahmen zur Untersuchung der Umweltmigration vom globalen Süden in den Norden, verknüpft mit den Paradigmen der Klimafinanzierung und der Erfolgswahrscheinlichkeit von Migration angesichts der Grenzüberwachung des Gastlandes. Beeinflusst von Brausmanns und Ddjajićs Studie (2022) zur Migrationsdynamik setzt diese Forschung drei Modelle ein.

Das erste Modell beschreibt die Vorteile, die Gastländer erzielen, wenn sie Umweltmaßnahmen gegenüber Grenzkontrollen priorisieren, was zu einem reduzierten Migrantenzustrom und Durchsetzungskosten führt und sowohl Quell- als auch Gastländer begünstigt. Die folgende Analyse führt budgetäre Einschränkungen ein und hebt das Gleichgewicht hervor, das Nationen zwischen Umweltmaßnahmen und Grenzkontrollausgaben finden müssen. Es wird betont, dass Minderungsmaßnahmen im Herkunftsland die Grenzkosten und die Migrantenanzahl senken könnten, während die Studie deren Wirksamkeit in Frage stellt.

Das abschließende Modell geht auf das Gleichgewicht zwischen Migrationsentscheidungen und Umweltmaßnahmen ein. Zentrale Erkenntnisse legen nahe, dass die Stabilität der Migrationsdynamik von spezifischen wirtschaftlichen Parametern abhängt, wie dem zukünftigen Diskontsatz des Landes und der Zuflussrate des Bestandes. Darüber hinaus können Umweltmaßnahmen die Wahrscheinlichkeit einer erfolgreichen Migration und den Gesamtbestand an Migranten erheblich verändern, abhängig von unterschiedlichen Klimafinanzierungsniveaus.

Abschließend verknüpft diese Arbeit theoretische Einsichten mit den realen Herausforderungen der klimabedingten Migration und befürwortet eine integrierte Kombination aus Politik, Finanzierung und Migration angesichts des globalen Klimawandels.

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It has been a privilege to work under her guidance, and I hope this work stands as a testament to the high standards of excellence she embodies and teaches her students.

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Chapter 1

Introduction

Human migration, influenced by factors such as economic opportunities and environmental conditions, has undergone a significant transformation with the onset of climate change. Phenomena like unpredictable weather patterns and challenges in agriculture are becoming primary drivers, pushing individuals to migrate within or outside their national borders (Reuveny and Moore, 2009). Such a transformative shift underscores a pressing problem: understanding and managing climate-induced migration. The present research seeks to investigate this problem.

Human migration has long been shaped by socio-economic and political factors. Today, environmental shifts, especially those driven by climate change, add another layer of complexity to the reasons for migration. This new phenomenon shifts our understanding of traditional migration theories.

Environmental risks, both from rapid climatic changes and human actions, are now considered significant drivers for migration. The Intergovernmental Panel on Climate Change (IPCC, 2014) points out the growing potential for environmentally-induced migration. Yet, predicting the scale and nature of these migrations is still challenging (Millock, 2015). The International Organization for Migration (2009) offers a broad label for this phenomenon: "environmental migrants" describing the people displaced by either sudden or gradual environmental changes. Such a broad categorization hints at the multi-layered relationship between the environment and migration decisions.

The idea of "environmental migration" has become popular also in discussions about international development. Important reports like the Stern Review and the UN's foundational report on climate change have warned about the large numbers of people migrating due to environmental changes, especially in developing countries, while keeping in mind that understanding the interplay of environmental changes and migration is not that straightforward (Beine and Parsons, 2015). This complexity is mirrored in the ongoing scholarly debate over the terminology surrounding migrants who are impacted by environmental variables. Although they are already in popular culture, terms like "climate refugees," "environmental migrants," and "environmental refugees" represent different difficulties and conflicts. Sudden natural disasters like Hurricane Katrina and the 2004 tsunami have brought public attention to the direct migration effects of environmental disruptions (Afifi and Warner, 2008). However, considering slow-onset events, Black et al. (2011) and Cattaneo et al. (2019) point toward the difficulties in categorizing particular groups as "environmental migrants" due to the complex factors that influence migration choices.

Environmental push factors span from natural disruptions, such as hurricanes and temperature anomalies to human-induced phenomena like deforestation and soil erosion. Even though these factors drive migration, the effectiveness of the factors is closely tied to the economic, social, and political contexts of the time (Millock, 2015). Adger et al. (2015) stress that while the environment plays a role, economic factors often become central in migration decisions. This is evident when looking closely at the impact of environmental changes on agriculture, especially in developing countries where agricultural production is essential for subsistence and livelihoods.

Increasing amount of evidence suggests a possible positive correlation between environmental disruptions and societal conflicts, particularly in cases of droughts and floods (Homer-Dixon, 1991). Adger et al. (2015) note that migration can sometimes precede conflict, but this relationship varies depending on the scale of analysis.

From a modeling perspective, while empirical studies flourish, there's a lack of detailed models on environmentally induced migration. Banzhaf and Walsh (2008) connect migration in California to air pollution, arguing that while the environment quality affects the economic output, its direct effect on personal well-being is not explored enough (Millock, 2015). Tawada and Sun (2010) present a model exploring how environmental conditions directly influence individual utility. In their model, they explore the urban workers' well-being impacted by productivity and by environmental degradation.

Migration theories have their roots in multiple disciplines, including economics, geography, political science and sociology (White, 2016; Wickramasinghe and Wimalaratana, 2016; O'Reilly, 2015). Zolberg (1989) suggests that adapting these theories to our changing world is vital. While climate change reshapes migration, more households consider moving as a solution and adaptation to environmental challenges (Antwi-Agyei and Nyantakyi-Frimpong, 2021). Ignoring the role of environmental factors in migration theories could cause a bias, leading to potentially inaccurate interpretations (Piguet, 2013; McLeman, 2014). Historically speaking, environmental dynamics have always influenced migration patterns (Hunter and Simon, 2023). For example, while trying to understand the mass migrations during America's Dust Bowl period, Hornbeck (2020) found that migrants from highly eroded regions tended to be "negatively selected" regarding education. These Dust Bowl migrants were younger, predominantly male, and had fewer educational years compared to their general migrant counterparts. Furthermore, despite the drastic environmental impacts and decline in agricultural land values, 1939 wage incomes for residents from more-eroded counties only showed small differences compared to their counterparts from less-eroded regions. This shows how strong and adaptable these communities were.

This inclusive, multidisciplinary view of environmental migration is also mentioned by other authors. As it's fundamental to understand environmental migration from a wider perspective, acknowledging the combined roles of environmental, socioeconomic, and political factors, migration decisions, even though often regarded as reactions to environmental challenges, which is a part of broader livelihood strategies, emphasizing adaptability require more nuanced understanding and work (Mueller et al., 2020; Entwisle, Verdery, and Williams, 2020). This perspective avoids oversimplification of migration as just a reaction to the environment (Hauer, Fussell, Mueller, et al., 2020).

Traditional theories often point out differences in labor demand and supply as key determinants of migration. However, these theories sometimes miss the deeper complexities in today's global setting especially considering climate change (Wickramasinghe & Wimalaratana, 2016). Migration systems theories offer a wider view, looking at culture, society, politics, and the environment as components of migration (Hunter & Simon, 2022). The World Systems Theory is a macro-level economic model that is particularly useful for understanding international migration flows, especially migrations from peripheral regions to core nations (Wallerstein, 1974). As Alvarado and Massey (2010) reveal, the rise of global capitalism in emerging economies can increase inequalities, thereby fuelling migration. This process is selective, where highly-skilled migrants from peripheral nations move to core countries, which causes their home countries to be held back in the development race.

Entities from core nations seeking opportunities in peripheral countries, often establish in peripheral countries for their cheaper labor and easier rules, which in the end causes internal migration (Villarreal and Hamilton, 2012). Lastly, while certain financial policies were conceived as financial solutions for countries burdened with heavy debts, they have also attracted a fair amount of criticism. Many believe these policies often benefit capitalist interests and neglect the development goals of the country itself (Alvarado & Massey, 2010). One of the obvious consequences of these policies is the transition to monocultural agriculture, leading to more land degradation and deforestation which in return has nurtured increased displacement in peripheral countries (McLeman, Schade, and Faist, 2016).

Climate change causes temperature changes, unpredictable rain, and more extreme weather events. These changes can lead to direct problems like diseases spreading at a fast pace or they can cause indirect problems, like hurting agriculture dependent economies. As a push factor for individuals to move to cities in their own countries or even to other countries due to economic pressures. However, at the macro level, it's hard and challenging to differentiate economically driven migration and environmentally induced movements.

As it has been discussed so far, migration doesn't have a one-size-fits-all explanation. In certain regions, like sub-Saharan Africa, climate change has already taken a toll on their economy, leading to shifts in migration dynamics. Even though these factors are clearly connected, there's a gap in studies that look at how environmental changes impact global migration.

Past studies on this topic haven't always provided clarity. Some research links environmental variables to increased migration, while others have found reduced or no significant correlation. It can be argued that many previous macroeconomic studies didn't pay enough attention to environmental determinants while investigating migration patterns. Beine and Parsons (2015) tried to address this gap. Their study combined various factors—economic, demographic, social, and political—with climatic elements like temperature changes and precipitation variables. One of their standout contributions was highlighting migrations within the Global South, offering insights into often overlooked South-South migration patterns, especially in contexts where agriculture is the main economic activity.

The findings from this study have revealed some very important information, such as: while long-term climate changes such as deviations from mean temperatures and rainfall, didn't have a big direct effect on global migration, short-term extreme events, especially natural disasters, show possible indirect effects. This was seen especially in migrations within the Global South. Countries relying heavily on farming or with limited water resources were more sensitive to long-term environmental changes.

This situation is reflected also in the discussions and theories. While in the past, discussions about migration mainly looked at issues like hunger, poverty, wars, and violations of human rights, now environmental reasons with the growing realization of its evolution and enormous effects are now getting more attention in migration research. (Afifi & Warner, 2008). Black et al. (2011) note about this shift and point out the past neglect of environmental factors in migration theories and emphasis the need of recognition of the influence of environmental changes on migration.

Afifi & Warner (2008) discuss that while environmental problems can be a driver for migration, they're usually combined with other reasons. For instance, a worsening environment can make it hard for people to earn a living. This can be due to poor farming lands, ecological problems, or natural disasters impacting work areas. On the other hand, Black et al. (2011) explained that it's better to see a network of factors leading to migration, rather than just one cause and its effect.

When studying the relationship between the environment and migration, unique methods are needed. Afifi & Warner (2008) employed a gravity regression model, integrating thirteen global environmental variables with other factors to analyze their collective influence on global human migration. Their work was groundbreaking because of the incorporation of environmental variables into their model, demonstrating a clear positive relationship between environmental degradation (especially soil quality and water availability) and migration flows.

Among all the theories and discussions about climate change and its effect on migration, some studies stand out. One such investigation, conducted by Cattaneo et al. (2019), explores the complex ways in which climatic changes may affect human migration. They emphasize the difficulty in distinguishing the effects of true climate change from those of merely climate fluctuation. While the former can be a sign of the potential effects of upcoming climatic changes, it is difficult to draw a clear connection between the two. Understanding this distinction is critical, especially considering the different consequences of slow-onset events like droughts and fast-onset events such as floods have on human mobility.

An important point from Cattaneo et al. (2019) is that in some circumstances, climate change represents a constraint to migration. Far from forcing people to move, climate change can prevent certain populations at risk from escaping danger, trapping them in exposed locations and vulnerable situations. This is because, the causes of each type of human mobility are highly contextual, depending on the history of migration and the dynamics of economic, political, demographic, social and environmental factors at the origin and destination. For example, while slow-onset events often lead to economically motivated voluntary migration, fast-onset events are more likely to cause involuntary, short-term displacements. However, determining a direct causality between climate change and migration is complex. Often, climate is just one of many reasons of migration determinants (Cattaneo et al., 2019).

Another report, "*Foresight: Migration and Global Environmental Change Final Project Report*

(2011)", looks at possible migration trends over the next 50 years, especially focusing on environmental changes. The report explains that while changes in the environment will indeed impact migration, also mentions who is moving only because of the environmental disruption is challenging, this is due to the fact that drivers of migration are intertwined and each has different interaction with another, Hence, this report as well points the other factors of migration and their interactions between each other.

Interestingly, the report shows that people might move to places that have environmental risks just as much as they might move away from them. This is concerning, especially since many more people are expected to live in flood risk areas in cities in Africa and Asia by 2060. As the environment starts affecting populations' livelihoods and putting them at risk of natural disasters, migration becomes a common solution. However, this type of migration has its own set of problems, such as how to plan these movements or deal with people forced to move due to big environmental disasters.

The report also highlights another significant point about populations who are "trapped" in places that are at risk in terms of environment but unable to move because of limited resources. Helping these people is a big challenge for decision-makers. Instead of only seeing migration as a problem caused by the environment, the report advocates migration to be a form of resilience to make people safer. If done right, migration can help populations get out of dangerous situations. This makes it a helpful tool, and not just a side effect of environmental changes.

Digging in the empirical area, contemporary studies are actively exploring the complex dynamics between climate fluctuations, with a spotlight on temperature alterations, and migratory trends. One key study by Bohra-Mishra, Oppenheimer, and Hsiang (2014) used 15 years of data from Indonesian families. They found that when temperatures rise above 25°C, many people decide to move for a long time. Their study shows that slow climate changes affect migration more than sudden big events. This is especially clear when looking at the economic implications, as areas like Indonesia see a drop in agricultural yield when the climate changes, compelling households to re-evaluate their continued residence and ponder over potential relocation.

Similarly, Cattaneo and Peri (2016) explored the effects of rising temperatures, especially regarding agricultural productivity. They found that temperature changes affect countries differently based on their economy. Very poor countries might see less movement because their populations don't have the financial means to migrate when farming gets less productive, conversely middle-income countries might see more people moving from the countryside to cities because of dropping in agriculture yield. This shift could inadvertently accelerate the macroeconomic growth of such nations.

Both studies agree that economic mechanisms play a big role in climate-induced migration. The reduction in household assets and agricultural yields due to increasing temperatures remains a significant theme (Bohra-Mishra et al., 2014). At the same time, the macroeconomic picture, like increasing poverty in the poorest countries or fostering GDPs of middle-income countries due to migration, is highlighted by Cattaneo and Peri (2016).

While empirical studies have advanced our understanding of effects of climate-migration, there are still some inconsistencies, for instance, specific temperature thresholds and their specific effect on migration. These differences show how complex the topic is and suggest we need more detailed, consistent research in future studies.

Shifting focus from general climate trends, recent studies have closely looked at how environmental changes impact people, especially when it comes to migration. Perch-Nielsen, Battig, and Imboden (2008) studied whether problems like long droughts, land degradation, or rising sea levels make people migrate. The emergence of terms like 'environmental refugees' is to describe this phenomenon. Yet, the debate in the academic world by some is focusing only on environmental reasons is too simple, especially ignoring human adaptability. When specific cases are examined, it's evident that the intersection of climate change and migration is not just dictated by environmental shifts but is deeply intertwined with human adaptive responses.

To illuminate the complex relationship between climate change and migration, Perch-Nielsen and his team (2008) created models to understand how floods and rising sea levels caused by climate change affect migration. Their research shows that an array of factors, including economic and social conditions, as well as alternative adaptation options influence the decision to migrate illustrating the complexities beyond conventional thinking. For example, while floods can force many people to leave, they might not be the main cause of mass migration due to climate change. However, the link between rising sea levels (caused by climate change) and migration is more direct. The main takeaway from their paper is that it is necessary to have both detailed case studies and broader arguments to truly understand this issue.

Then, Reuveny and Moore (2009) studied how a worsening environment makes people migrate, especially towards developed countries. Their study points out that deteriorating environmental conditions, like those caused by climate change, play a significant role in why people move. Individuals affected by environmental decline tend to move to developed nations. However, this migration pattern can present challenges for these countries, affecting things like their resources, social order, and even national security. Importantly, the study doesn't narrow down environmental degradation as the sole cause for migration. It acknowledges the complex and intertwined reasons behind migration decisions, including economic factors, political conditions, and socio-historical contexts. To support these claims, the study looks at many examples and uses data from national surveys to better understand why masses migrate because of the environmental conditions and associated conflicts.

Marchiori and Schumacher (2011) explore the connection between international migration and climate change, constituting a theoretical model. The authors ground their research in a two-country, general equilibrium, overlapping generations model, inspired by Galor (1986), to systematically analyze the welfare implications of migration when climate change considerably affects overall welfare. The model's foundation rests on the notion that individuals compare prospective welfare in their home region to potential benefits in another, leading them to migrate if they anticipate better conditions elsewhere.

Their key findings suggest a significant link between climate shifts and international migration patterns. Specifically, even marginal impacts of climate change can lead to a substantial surge in migration numbers. They found that a minor climate-induced reduction in the productivity of southern regions by roughly 5% could result in four times increase in migration numbers. Yet, their empirical studies suggest that southern productivity could face more than a 5% decline in the foreseeable future, emphasizing the potential for migration to drastically alter global structures if not appropriately managed by international policies. Additionally, the research draws attention to the critical nature of the policies chosen by northern regions, specifically the US and Europe, in response to these challenges. The authors argue that these decisions will depend on the weight the northern regions place on migration, environmental concerns, and inequality. They conclude with a pointed observation: while the long-term implications of such policies are crucial, understanding their short-term effects is equally vital.

In their influential work on the dynamics of mass migration, Brausmann and Dijajic (2022) explain the nature of mass migration induced by factors such as natural disasters, climate change, and armed conflicts. Employing a theoretical approach due to the scarcity of literature on the topic, the authors design a model that underlines the many-sided interactions between migrants, who are driven primarily by survival instincts, and the authorities of the destination country faced with increasing migration pressures. The model takes into consideration the challenges posed by geographic barriers, criminals, and rigid border control measures, all of which often necessitate migrants to seek the services of human smugglers. Differing from purely economically motivated migration, this study necessitates a dynamic analytical framework capable of addressing stability-related questions, discerning factors that can stabilize or destabilize migration flows, and understanding how to preserve the structural integrity of border-control measures. Brausmann and Dijajic's findings are both illuminative and applicable. Key among these is the revelation that the speed at which border-control efforts adjust to increasing pressures is pivotal in determining both the fiscal implications and the time required for the destination country to stabilize migration flows. Importantly, a slower response rate imposes more resources in the long run. By analyzing specific cases, such as the EU-Turkey agreement of 2016, the study also underscores the effectiveness of criminalizing human smuggling activities in transit countries as a way of strengthening border-control measures in the destination country. Furthermore, the research sheds light on the influential role of diasporas in exacerbating migration flows and increasing border-control spending. Notably, while the simulations employed are primarily based on the Syrian refugee crisis, the authors urge a cautious interpretation of results, advocating for future research to focus on precise parameter estimation and a deeper exploration into the behavioral expectations of migrants and policy changes in host countries.

After searching and reading related literature I didn't see a mathematical model that is about environmental migration from global south to global north integrating climate finance (abatement) and successful migration probability through border control spending. I wanted to fill this gap in the theoretical realm and shed light for future research.

Building on Brausmann and Djajić (2022), which mainly examines the association between border spending and migration success, this thesis seeks to provide a fresh perspective. Recognizing the distinctions that climate change introduces to migration, there's a significant need to evolve over Djajić and Brausmann's models. For this purpose, I have undertaken an investigation into the interaction between border enforcement and mitigation efforts. I found out that climate finance can reduce the border enforcement spending, the first model suggests a decrease in both border control spending and stock of migrants. The second model implies that for a given budget allocating into abatement will reduce the border control spending even though its effectiveness is low. Extending into optimality, the third model suggests there will be larger stock for higher probability of passing the border. However, the probability will decrease against increasing stock of migrants. Furthermore, abatement also plays a role in decreasing both the probability and the stock. Another point is that the stability of the setups is fragile meaning as only certain policy interventions might lead to desired outcomes. When the Host country pledges for a fixed abatement, the model suggests similar results depending on the level of the pledge. For a higher pledge, the stock and the probability will be lower, while isolated, the probability and the stock are inversely correlated. In the following sections, the results of this study will be explained in more detail.

To navigate through this study, the upcoming sections theoretical framework and model development will prepare the desired environment for modelling. In the following section, three models will be introduced: the first model exploring the impact of climate on migration and how host countries can fund mitigation strategies, while second considers the budgetary constraints nations face when choosing between climate mitigation and border control, and with the third model the mathematical dynamics of migration when considering abatement measures will be explored. My results aim to provide insights for policy-making in this rapidly changing environment, bridging theoretical understanding with real-world migration challenges due to climate change.

Chapter 2

Theoretical Framework

The study of migration, particularly in the context of changing global climatic conditions, is not an independent exercise. Based on decades of research, theories, and models that aim to shed light on human movement and its varied determinants. This chapter outlines the theoretical backbone upon which the subsequent model development is based. It investigates the basic assumptions, foundational principles, and the essential role of the Brausmann and Djajić's model as the starting point for this research.

Basic Assumptions

Before exploring the specifics of the models, it's important to establish the fundamental assumptions shaping this research:

- **Migration as Rational Choice:** Migrants make decisions based on a combination of push-pull factors, weighing potential risks against expected benefits.
- **Border Control Spending:** Directly impacts migrants' border-crossing probability.
- **Abatement as Rational Choice:** Host countries decide on abatement expenditure based on utility which depends on numbers of successfully passing migrants relative to a desired level and amount of abatement spent out of pocket.
- **Climate Change as Push Factor:** As environmental conditions deteriorate, more individuals are compelled to move out of necessity.
- **Two-Country Scenario:** A simplified representation of the Global North and South, enabling a focus on core dynamics without complexities of sophistic geopolitics.

Migration and Economics: A Brief Overview

Economic theories have long engaged with migration, treating it as a decision based on cost-benefit analysis. At its core, a potential migrant evaluates the economic conditions of the home country (push factors) against those of a potential destination (pull factors). While this is a simplification, the economic rationale provides a foundation to understand more complex migratory motivations. While it's important to understand migration through micro-level decisions, when we zoom out to a macro perspective, migration begins to reveal patterns, dynamics, and equilibria that are essential for policy-makers and nations at large.

Migration as a Macroeconomic Phenomenon

At a macro level, migration can significantly influence:

- **Labor Markets:** The inflow or outflow of migrants can alter the labor supply, potentially influencing wages, employment rates, and even the skill composition of the workforce.
- **Economic Growth:** Migration can influence the growth trajectories of both source and destination countries. Remittances sent back home can boost the economies of source countries, while destination countries can benefit from an increased labor force, potentially filling gaps in sectors facing shortages.
- **Fiscal Impact:** Migrants contribute to tax revenues and demand public services, influencing the fiscal balance of a country.

Dynamics and Steady States

From a macro perspective, the study of migration, particularly in dynamic systems, often centers around the concept of a "steady state." This is a situation in which, even with ongoing migration processes, certain macroeconomic variables remain stable or change at a constant rate. Finding these steady states helps in understanding:

- **Migration Equilibria:** Identifying points where the inflow of migrants matches the outflow, or where the push-pull factors from both source and destination countries balance each other out.
- **Economic Stabilization:** A steady state can hint at periods of economic stabilization, where the effects of migration no longer induce significant changes in macroeconomic indicators.
- **Policy Implications:** For policymakers, understanding these steady states can offer insights into when and how to intervene to either maintain the state or shift the system towards a more desirable equilibrium.

Economics of Borders and Migration Dynamics

One of the key macro-level considerations in migration studies is the economic implications of borders. Policies related to border controls, tariffs, and even trade agreements can influence migration flows. The cost of enforcing borders, the probability of successful migration, and the potential economic benefits upon successful migration are all intertwined in a complex web of cause-and-effect.

Economic theories of migration, when viewed from a macro lens, shed light on broader patterns, equilibria, and dynamics that individual-level analyses might miss. As global issues like climate change introduce new challenges and variables into the mix, a macro perspective becomes ever more crucial to understand the complicated relationship of economic and migratory forces.

Climate Change and Migration

In recent years, the addition of climate change to the migration discourse has added layers of complexity to traditional economic theories. Environmental degradation, loss of livelihood, and heightened resource scarcity contribute to the push factors, often in non-linear and unpredictable ways. Theories like Environmental Determinism and Neo-Malthusian perspectives can offer insights into these complex relationships. Research by Marchiori and Schumacher (2009) utilized a two-country, general equilibrium, overlapping generations model to investigate the relationship between climate change and international migration, focusing on how shifts in climate can affect individual decisions to migrate. The study highlights the significant role of policies in managing potential large-scale migrations.

Brausmann and Djajić's Model: A Starting Point

Brausmann and Djajić's model from the article "Dynamics of Mass Migration" offers a crucial foundation for this research. The model emphasizes:

- **Border Spending:** The financial efforts made by countries to either fortify their borders or to streamline legal migration pathways.
- **Probability of Passing the Border:** Directly influenced by border spending, this parameter determines the likelihood of a migrant successfully crossing into another country.
- **Stock of Migrants:** The accumulated number of individuals wishing to migrate, influenced by both internal and external factors.

While their model offers robust insights into migration dynamics, the current global scenario necessitates a more detailed examination that incorporates the persistent issue of climate change.

Rationale for a Two-Country Scenario

A two-country model, representative of the Global North and South, allows for:

- **Simplification:** Streamlines complex global migration dynamics into a manageable and analytical format.
- **Focus on Core Dynamics:** Emphasizes the fundamental interactions between developed and developing nations, especially concerning climate change and migration.

- **Versatility:** Despite its simplification, the model retains the flexibility to be adapted and interpreted in various real-world contexts, including conflicts and political instability.

The theoretical framework serves as the foundational cornerstone for this investigation. It combines migration studies with the challenges presented by global climate change. This merger establishes the context for the following introduction of the three models. By understanding the assumptions, theories, and foundational models, readers are better equipped to grasp the differences and significance of the forthcoming analytical exploration.

Chapter 3

Model Development

Building upon the foundational model from the *Dynamics of Mass Migration* paper, I initiated an exploration centered on the ramifications of alterations in the parameter C which stands for climate change or conflict factor. The paper already offers insights into this parameter, but my approach introduces a more focused interpretation. Specifically, I've associated C with the effects of climate change (or pollution) in the Source country.

A notable premise in my modifications is the ongoing trend of worsening climate change. The potential consequences of this trend are sophisticated: not only does it intensify environmental challenges in the Source country, but it also causes a rise in environmental migration. This rise, in turn, intensifies the demand for border control resources. Therefore, in these revised models, the Host country's proactive measures to mitigate the adverse impacts of climate change in the Source country emerge as a strategy. By addressing one of the root causes, environmental degradation, these models not only showcase an effort towards global sustainability but also potentially limit the rising trend in environmental migration, offering a dual benefit.

Equations from the Original Model:

1. **Cost of Migration:**

   $$K = aR + b\alpha S$$

   Where:

   - K: Cost of Migration
   - a: Coefficient denoting the effect of border control
   - R: Resources allocated for border control
   - b: Coefficient for migration attempts
   - α: Fraction of stock representing migration attempts
   - S: Stock of migrants

2. **Resources Per Migrant for Border Control:**

$$r = \frac{R}{\alpha S}$$

3. **Probability of Crossing the Border:**

$$\pi = e^{-dr}$$

Where:

- π: Probability of a migrant successfully crossing the border
- d: Coefficient

4. **Number of New Arrivals:**

$$\sigma = C(\gamma\pi - \delta K)$$

Where:

- σ: Number of new arrivals
- C: Driving force stemming from climate or conflict scenarios
- γ: Coefficient
- δ: Coefficient

This equation factors in the impetus caused by climate change, migration costs and the probability of crossing.

5. **Rate of Change in the Migrant Stock:**

$$\dot{S} = \sigma - \pi\alpha S$$

Here, the rate is influenced by the influx of new arrivals and by the outflow of successful migrants.

6. **Change in Resources Allocated for Border Control:**

$$\dot{R} = \phi(\pi\alpha S - \bar{F})$$

Where:

- ϕ: Coefficient denoting spending per excess migrant
- $\bar{F}$: Threshold number of migrants the Host country deems acceptable. Numbers beyond this may pose societal challenges and are thus seen as undesired.

How original model works: The original model takes drive of climate change/conflict into account as parameter, $C = 1$, while observing the changes in migrant stock, $\dot{S}$, and resources allocated for border control, $\dot{R}$. Change in both accommodates the change in probability of crossing the border and other variables. As seen in the Figure 3.1(a), for an increasing border control spending, stock of migrants first increases, then reaches to its peak and then goes down. Where the two lines cross, we have a steady state that there is no change in stock of migrants and border control spending, i.e. $\dot{S} = \dot{R} = 0$. Observe that the equilibrium presented in the figure is stable. A shock originating from external factors, like alterations in the conditions of the Source country or modifications in the immigration policy of the Host country, prompts adjustments in S and R, which subsequently leading these variables to their new equilibrium levels in the long run (Brausmann and Djajić, 2022).

3.1 Model 1: Integrating Pollution Abatement

Function Formulation

The "push" factor, compelling inhabitants of the Source country to leave, can be represented by the parameter C, symbolizing the level of environmental degradation or pollution. A critical factor in this model is the introduction of abatement, A, and its effect on C.

The abatement function, $C(A)$, captures the essence of diminishing returns: as more is invested in abatement, each subsequent unit has a decreasing effect on pollution reduction. We also acknowledge that there exists an inevitable minimum level of pollution, unaffected by abatement.

The proposed function for $C(A)$ is given by:

$$C(A) = C_{\min} + (C_0 - C_{\min})e^{-\beta A} \tag{3.1}$$

This function is a decreasing function of A, asymptotically approaching $C_{\min}$ as A grows.

By integrating the above function, the σ function from the original model is reformulated as:

$$\sigma = C(A)(\gamma\pi - \delta K) \tag{3.2}$$

Choosing Parameter Values Setting $C_{\min}$ requires care. Even with intense abatement efforts, it's unrealistic to assume complete eradication of pollution, more so when considering a broader spectrum of environmental degradation. Hence, $C_{\min}$ symbolizes the baseline pollution in an almost untouched environment. Given that pollution levels can be measured differently, if a scale of 0 (no pollution) to 1 (status quo) is adopted and C_0 is set to 1, $C_{\min}$ could hypothetically be 0.01. Holding other variables constant, choosing this value for $C_{\min}$ would signify that new arrivals would be 1% of the current number when $C_0 = 1$, incentivizing the Host country to aim for this level.

Calibration and Practical Validation

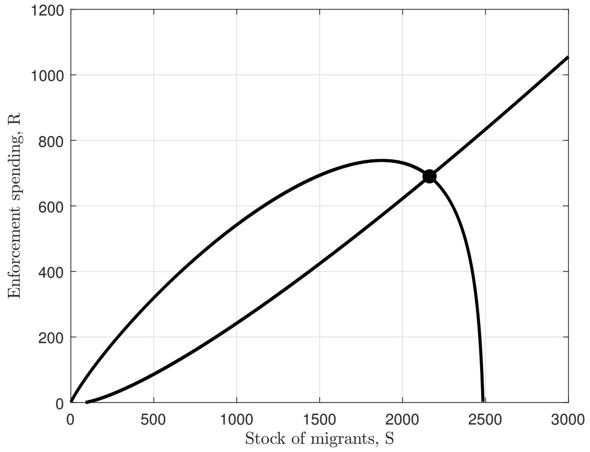
To ensure the model's practical relevance, data from real-world climate finance initiatives was incorporated. For instance, at COP15 in 2009, developed nations committed to an annual sum of \$100 billion towards both climate adaptation and mitigation. Although initially planned for 2020, this goal was shifted to 2025. As of 2020, the aggregate level stood at \$83.3 billion, with countries like Japan, France, and Germany reporting contributions of \$11.8 billion, \$7.3 billion, and \$6.7 billion, respectively. This translates to a collective daily commitment of approximately \$273.972.603.

Assuming a bi-regional model (representing the global North and South), with an average annual climate finance of \$7.5 billion[1], it can be anticipated that C will approximate to the $C_{\min}$ level. With

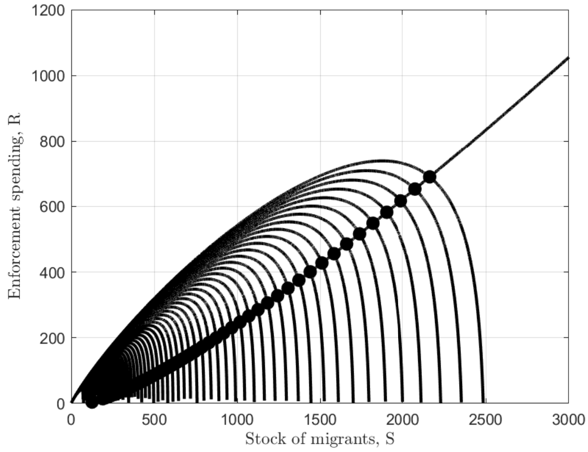
[1]Number of the host countries who will provide climate finance according to COP15 is assumed to be around 13 (thinking of the G20 and yet of 19 countries and EU, some of the countries will be reluctant or not affected by environmental migration), also number of the receivers (Source country) can differ depending on definition; here in the model we only need to provide transfer of money to countries that are source of migration and risk for developed countries. As a note: in 2020, according to the report by OECD there are 39 developed countries and 162 developing countries.

the daily spending calculated to be around \$20,550,000, β will be calibrated to 0.00134.

Graphical Representation



(a) Graphical representation of original model showing steady states where $A = 0$ and $C = 1$.



(b) Graphical representation post calibration, showing steady states for varying A values.

Figure 3.1: Graph of Stock of Migrants versus Enforcement Spending before and after Abatement

In the Figure 3.1(a) we have the graph of stock of migrants against enforcement spending in the axis. In the basis condition that there is no abatement and climate conditions do not vary, we acquire a steady state where there is no rate of change in both variables as mentioned above.

By the Figure 3.1(b), we can compare to the Figure 3.1(a) the change in behavior of enforcement spending and stock of migrants curves. In this figure, please note that the model incorporates A as an exogenous variable and answers the question of how the steady state would change when A is increased. While A grows by \$41100 in each iteration, the curve of stock of migrants at the top forms followed by succeeding curves underneath it. By each curve a new steady state is achieved in intersection points, where each of them has lower value of both stock of migrants, S, and enforcement spending, R. Here, as the main point, it can be argued that by increasing abatement it is possible to have a lower steady state in stock of migrants and enforcement spending plane. Moreover, as the original model checks and validates stability, it can be also argued that newly found steady states will be stable.

Considering Abatement at the Expense of Border Control Spending

In this section, we explore the dynamics when abatement efforts, A, are funded by reallocating resources originally meant for border control spending, R. This perspective offers insights into the possible outcomes if the Host country diverts funds from border control to improve environmental conditions in the Source country.

Equations governing this section:

$$C(A) = C_{min} + (C_0 - C_{min})\, e^{-\beta A}$$

$$\sigma = C(A)(\gamma\pi - \delta K)$$
$$\dot{R} = \phi(\pi\alpha S - \bar{F}) - A, \ \rho'(.) > 0$$

As observed in this section, the function governing the rate of change in enforcement spending, $\dot{R}$, has been modified to include abatement at the expense of border control expenditures.

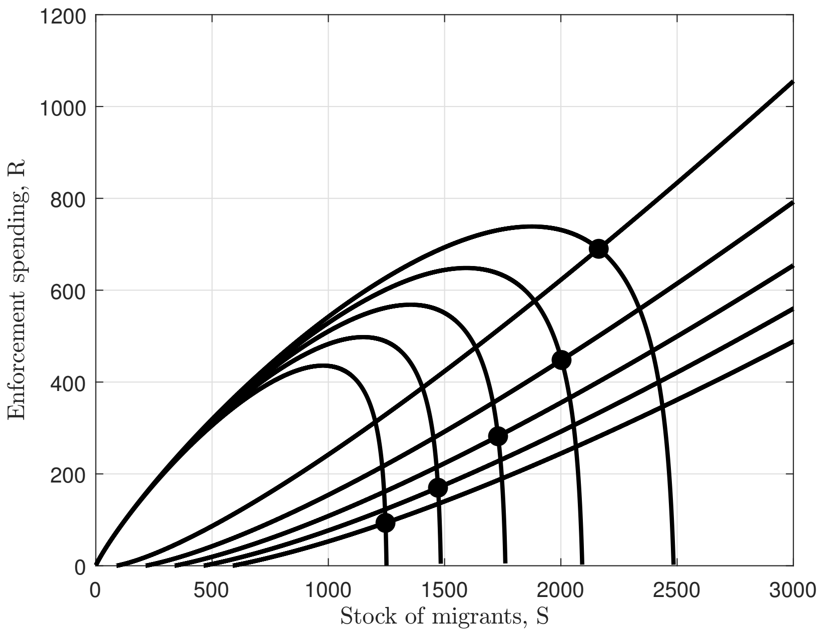


Figure 3.2: Steady states in response to increasing climate finance.

The figure 3.2 indicates that financing abatement at the expense of border control leads to shifts in both the stock of migrants and border control spending curves. These curves move downward, resulting in lower steady states. Comparing to the Figure 3.1(b), we note that the decline in the steady state stock and border enforcement expenditure happens at a lower rate. This is because now there is a trade-off between R and A. With such an outcome we can argue mutual benefits for both countries, assuming Source country has an increasing utility in decreasing stock of migrants, for instance, when the Source country experiences brain drain losing its skilled workforce.

Defining Host Country's Objective The above graphical representations help understand how varying R and A values influence migrant stocks. However, to clearly define the Host country's objective, we encounter a bifurcation:

1. Maintain the rate of migrants successfully crossing the border at a given $\bar{F}$. In the original model $\bar{F}$ is set at 0.89. This figure is based on Eurostat (2021) data, which indicates that asylum seekers in the EU increased from 225,000 in 2008 to 594,000 in 2014, largely due to conflicts in Syria and Afghanistan. Averaging out the data from this period, there were 325,000 asylum seekers each year or 890 per day. Thus, the daily rate of 0.89 (in thousands) is set as the benchmark for desired migrant inflows (Brausmann and Djajić, 2022).

2. Stabilize the migrant stock, S (in this scenario, 89,000 migrants), such that eventually, the Host country doesn't allocate any resources to border control ($R = 0$). Assuming only 1% of the stock successfully crosses the border, both scenarios yield similar outcomes for the Host country.

As evidenced in the previous analysis, after numerous iterations, the Host country's border control expenditure R potentially converges to zero.

Initial Abatement Consideration It's vital to note that while the initial conditions didn't account for any abatement, in reality, developed countries have committed to climate finance. Therefore, it would be inaccurate to assume an initial abatement of zero, $A_0 \neq 0$. For the sake of this model, calibrated with 2015 Syrian refugee crisis data from the original study, the initial abatement is assumed to be zero $A_0 = 0$ which gives the outcome of the original model with $C = 1$ from the study (Brausmann and Djajić, 2022).

3.2 Model 2: Role of Budget Constraints

In this section, we introduce a model that contemplates the role of budget constraints in the context of border control and climate change abatement. Main point of this model is the intricate balance the Host country must strike between allocating funds towards border control and investing in efforts to reduce pollution and mitigate climate change. In other words the center of discussion is the budget restriction, expressed as $R + A \leq B$. Here, R denotes spending on border control, A symbolizes abatement funding targeting pollution reduction, and B represents the total budget.

For an illustrative touchpoint, European border control spending can be examined. The budgets reserved for Frontex in the years 2021, 2022, and 2023 were €535 M, €754 M, and €839 M, respectively[2]. In our case, 2021 Frontex budget is used for calibration.

Our previous model introduced $C(A)$ to depict the pollution level, with A reflecting the impact of pollution reduction efforts on this level. Consequently, the current model modifies the equation of R to incorporate the budgetary constraints. A critical assumption underpinning this model is that the Host country invariably utilizes its entire budget. This translates to the equation: $R = B - A$. From this relationship, equation of rate of change in the resources allocated for the enforcement of border control policies[3] evolves as: $\dot{R} = \rho(\pi(R,\ \alpha S)\alpha S - \bar{F}),\ \rho'(.) > 0,\ R = B - A$.

Given this structure, the Host country's budgetary decisions have immediate implications: greater expenditure on pollution abatement always reduces funds available for border control, and the converse holds true. A pivotal query this model aims to address revolves around the optimal budgetary split between A and R, especially given a predetermined number of desired migration flow, $\bar{F}$.

However, a caveat arises in the process of model construction. While we can implicitly define abatement A via the budget constraint (i.e., $A = B - R$), and thus aim to find the steady state (SS) of R which in turn defines A, interpreting the most effective budget allocation remains difficult.

That being said, the primary equations governing this model are:

$$B \geq R + A, \text{ utilizing entire budget } \rightarrow\ B = R + A$$
$$\dot{R} = \rho\left(\pi\left(R, \alpha S\right)\alpha S - \bar{F}\right), \quad R = B - A$$

We can substitute the R with $B - A$ in the function containing R defined in Model Development which effect the schedules of both enforcement spending and stock of migrants.

After utilizing these equations and subsequent calibrations, we present the following graph comparing three distinct concave curves.

The graph can be interpreted as follows:

- The topmost curve delineates a scenario where the budget is exclusively allocated for border enforcement.

[2]€2.1 billion for protecting our borders, of which €1.1 billion for the Integrated Border Management Fund (IBMF), and €839 million (total EU contribution) for the European Border and Coast Guard Agency (Frontex) can be accessible at https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3473, for previous years: https://www.statista.com/statistics/973052/annual-budget-frontex-eu

[3]Brausmann and Djajić, 2022.

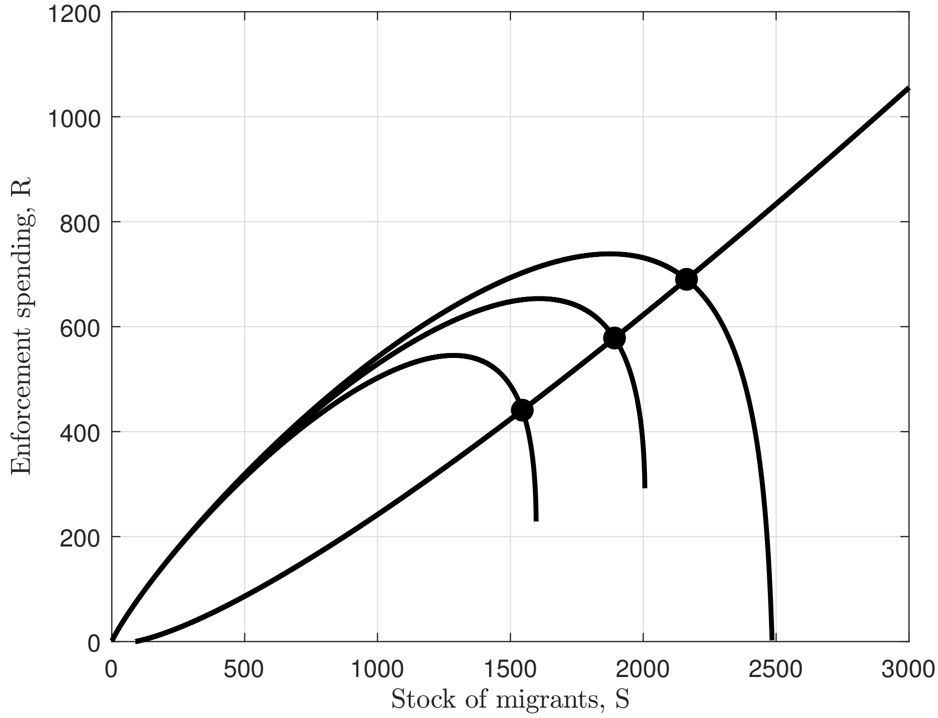


Figure 3.3: Comparison of budget allocation scenarios.

- The middle curve demonstrates the scenario when all the budget is distributed between border enforcement and abatement.
- The last curve portrays a hypothetical scenario where the budget is doubled and then split between enforcement and abatement.

For the three scenarios, numerical results of steady states for R, A, and S are as follows:

- Top curve (No abatement, control scenario): $R = 0.6902$, A (excess) = 0.8770, $S = 2.1629$
- Middle curve (Budget constraint between A and R): $R = 0.5255$, $A = 1.0416$, $S = 1.7605$
- Last curve (Use of double-budget scenario): $R = 0.3108$, $A = 2.8235$, $S = 1.1959$

In a hypothetical scenario with an increased border passing probability shock of $d = 0.075$, we get the following steady states:

- Top curve (No abatement, control scenario): $R = 0.9178$, A (excess) = 2.2164, $S = 2.1588$
- Middle curve (Budget constraint between A and R): $R = 0.7418$, $A = 0.8253$, $S = 1.8376$
- Bottom curve (Use of double-budget scenario):$R = 0.4296$, $A = 2.7047$, $S = 1.2276$

From the calculations and in the graph, it is noticeable that the curve for Stock of migrants is shifted up, and including abatement in the scenario highlights a larger difference between steady

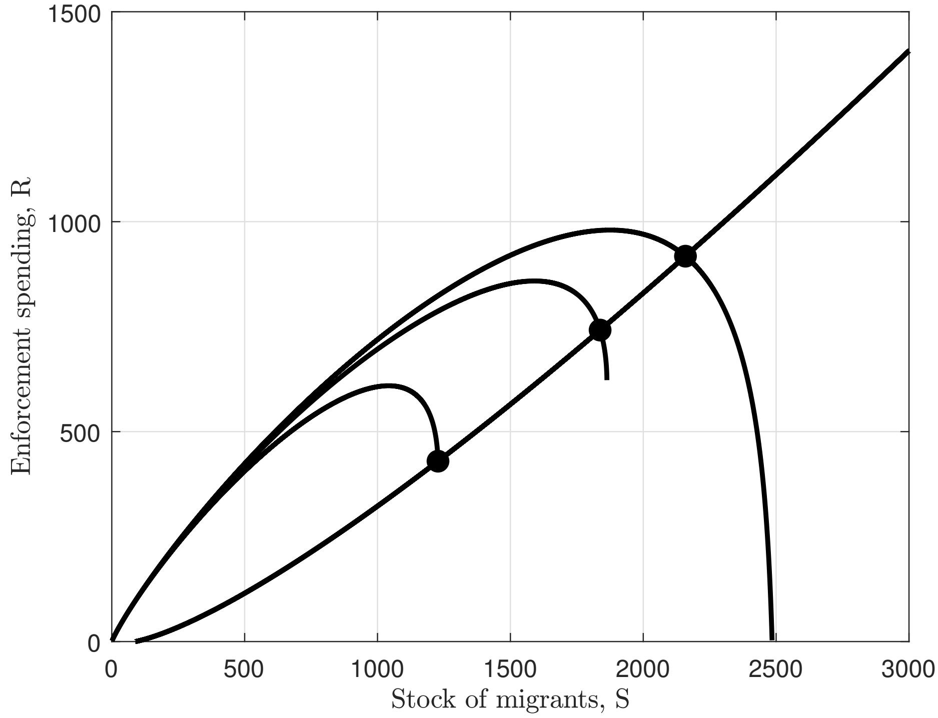


Figure 3.4: Comparison of budget allocation scenario with increased probability.

states. If there is no abatement, the steady state of the stock increases with a larger d, which is to be expected. However, when a possibility of abatement is introduced, the SS of the stock falls, while border enforcement increases.

3.3 Model 3: Optimal Abatement

The original model, as discussed, was more deterministic. It primarily took into account border control spending and stock of migrants based on various factors, including the success rate of crossing and the push factor related to climate change. This model gives a direct relationship between the variables: if border control spending is increased, the success rate of migration changes, which in turn affects the stock of migrants. It's more of a "cause and effect" setup, without seeking what's best or optimal for any party involved.

However, the third model introduces the concept of optimality by explicitly considering the objective function of the host country. Instead of just seeing the cause-effect relationships between variables, the third model is designed to achieve a certain objective, i.e. to maximize a utility function. It should be noted that in this model instead of incorporating border control spending, the probability of a migrant successfully crossing the border is used. In this way, enforcement spending, R, is excluded from all the equations to have undivided attention on the variable π, the probability of successful border crossing. Interpretations about enforcement spending can be made later taking the probability into consideration.

While utility in economics is often referred to the satisfaction or benefit derived by consuming a product, here we consider only the Host country preferences. In this model, the utility function is introduced to quantify the benefits and costs associated with different levels of migration and the probability of crossing. The objective is to find a steady state where this utility is optimized.

To incorporate this objective, the Hamiltonian approach is used. This mathematical tool combines the original system equations with the introduced utility to find steady-state values that optimize the utility function. The Hamiltonian will give conditions for optimality, considering both the system dynamics and the utility.

With the introduction of utility, this model seeks not just finding out what happens when certain parameters change, but finding the best possible outcome given the constraints.

So in short, in this section we introduce the utility to find optimality for steady state values, so that we can optimize an objective function. This makes the model more suited for policy decisions where one wants to know the best course of action, not just the outcome of actions.

We start with a setup with abatement in Model 3.1, and simplify it in Model 3.2.

3.3.1 A Setup with Utility Function and Diminishing Returns to Abatement

In order to determine the optimal abatement value, A, we need to optimize an objective function. To do so, we need to define the necessary equations. Let's assume the excess amount over the acceptable threshold of migrants will cause disutility, painted in $u(X) = -\frac{1}{2}X^2$, X being the excess, i.e. $X = \alpha\pi S - \bar{F}$. This utility function represents the disutility caused by the difference between number of migrants successfully passing the border and threshold of acceptable number of new migrants in Host country.

For this setup let's define the utility of abatement as disutility for the Host country as spending for another country for an indirect benefit is disliked. For this reason, we hypothetically define the utility function as $\nu(A) = \frac{A^2}{2}$ and conclusive utility function will become: $\omega(X,A) = u(X) - \nu(A)$

Abatement will have an effect on the rate of change in stock of migrants, through the variable n depicting the rate of inflow to the stock of migrants, abatement will have an decreasing effect on it, considering an initial value without abatement, $\bar{n}$, n can be redefined as $n(A) = \frac{\bar{n}}{A+1}$. A simple yet effective equation finely representing a real-world scenario with diminishing returns of abatement. After this, we can define the rate of change in stock of migrants, $\dot{S}$, as follows $(n(A) - \alpha\pi)S$, where "$\alpha\pi$" is the rate of outflow from the stock of migrants.

By $\dot{S} = (n(A) - \alpha\pi)S$, we have a restriction on $n(A)$ and α that $n(A)$ should be always smaller than α, so, $\dot{S}$ can take positive and negative values. And let's assume S will be always positive, discarding $S = 0$ for a healthy discussion.

Now we can define the objective function. We want to maximize the present value of the lifetime welfare (utility) of the Host country. Therefore, we'll integrate the utility over time, while discounting future utilities at rate δ:

$$\mathscr{J} = \int_0^\infty e^{-\delta t} \omega(X(t), A(t)) dt \tag{3.3}$$

Given the utility function:

$$\omega(X,A) = u(X) - \nu(A)$$
$$\omega(X,A) = -\frac{1}{2}X^2 - \frac{A^2}{2}$$

and

$$X(t) = \alpha\pi(t)S(t) - \bar{F} \tag{3.4}$$

Our objective becomes:

$$\mathscr{J} = \int_0^\infty e^{-\delta t} \left(-\frac{1}{2}(\alpha\pi(t)S(t) - \bar{F})^2 - \frac{A^2(t)}{2} \right) dt \tag{3.5}$$

Given the dynamics of S:

$$\dot{S}(t) = (n(t) - \alpha\pi(t))S(t) \tag{3.6}$$

where, as mentioned, $n < \alpha$.

The aim is to find the optimal policy π^*, A^* and trajectory S^* that maximizes $\mathscr{J}$ subject to the dynamical system and the constraints. To determine how the Host country will act to maximize its welfare, we utilize a mathematical approach called optimal control theory. Here, we focus on an equation called the Hamiltonian, which helps us understand the dynamics of the system and find optimal policy paths. The Hamiltonian combines current utilities with expected future utilities. The method incorporates calculus of variations to find the paths for the control and state variables that maximize the objective function. We will use an adjoint system of differential equations which come from differentiating the Hamiltonian with respect to the state variables. This helps us find the adjoint variables λ and provides a system of equations that we can solve simultaneously with the original dynamical system to get the optimal control π^*.

Using the provided information, we can construct our Hamiltonian (which combines the immediate utility and the dynamics weighted by the adjoint variable λ) to solve optimal control for the dynamical system:

$$H = \omega(X,A) + \lambda[(n(A) - \alpha\pi)S] \tag{3.7}$$

$$H = u(X) - \nu(A) + \lambda[(n(A) - \alpha\pi)S]$$
$$H = -\frac{1}{2}X^2 - \frac{A^2}{2} + \lambda[(\frac{\bar{n}}{A+1} - \alpha\pi)S]$$

Let's define our variables in Hamiltonian:

- Control variable: π and A
- State variable: S
- Co-state: λ

The goal of the Hamiltonian optimization process is to identify the optimal strategies or controls, in our case, the optimal abatement value A and probability π. Our main aim is to find the optimal rate of abatement (A) which minimizes the disutility caused by excess migrants crossing the border while accounting for the disutility of spending on abatement. The Hamiltonian (H) combines these utilities and embeds the system dynamics. It helps us evaluate the instantaneous net benefit (or utility) of the system for given values of controls and states.

We now derive first-order conditions for an optimal path using calculus. These conditions are found by taking derivatives of the Hamiltonian with respect to state and control variables, yielding crucial equations:

$$\text{Derivative wrt } \pi : -(\alpha\pi S - \bar{F})\alpha S - \lambda\alpha S = 0$$

The derivative wrt π tells us how the optimal border-crossing probability should be set given the current stock of migrants and abatement.

Derivative of u wrt X is $u_X = -(\alpha\pi S - \bar{F})$. So, by substitution:

$$u_X\alpha S - \lambda\alpha S = 0 \quad \rightarrow \quad \lambda = u_X \tag{3.8}$$

$$\text{Derivative wrt } S: u_X \frac{\partial X}{\partial S} + \lambda(n - \alpha\pi) = \delta\lambda - \dot{\lambda} \tag{3.9}$$

The equation for S describes the dynamics of migrant stock and helps determine its future path.

$$\text{Derivative wrt } A: -v_A + \lambda n_A S = 0 \quad \rightarrow \quad v_A = \lambda n_A S = u_X n_A S \tag{3.10}$$

The equation for A guides the optimal setting for abatement, considering its direct cost and its effectiveness in controlling migrant inflows.

Integrating (3.8) and (3.9), $\lambda \frac{\partial X}{\partial S} + \lambda(n - \alpha\pi) = \delta\lambda - \dot{\lambda} | : \lambda$

$$\frac{\partial X}{\partial S} + (n - \alpha\pi) = \delta - \hat{\lambda} \quad \rightarrow \quad \alpha\pi + n - \alpha\pi = \delta - \hat{\lambda} = n \quad \rightarrow \quad \hat{\lambda} = \delta - n \tag{3.11}$$

In SS, $\hat{\lambda} = 0 \quad \rightarrow \quad n = \delta \quad \rightarrow \quad A^{SS} = A(\delta)$

Here we find that steady state of A is dependent on δ.

$$n^{SS}(A) = \delta \quad \rightarrow \quad \bar{n}/(A+1) = \delta \quad \rightarrow \quad A^{SS} = \frac{\bar{n}}{\delta} - 1 \tag{3.12}$$

Here by above equation we find steady state function of abatement, A.

$$\text{In SS, } \dot{S} = 0 \quad \rightarrow \quad n = \alpha\pi \quad \rightarrow \quad \pi^{SS} = \frac{\delta}{\alpha} \tag{3.13}$$

Since the rate of change in steady state is 0, we use it to derive the steady state equilibrium of the probability of successful border-crossing, π.

Hence, a restriction arise from (3.12), since A must be non-negative, then $\frac{\bar{n}}{\delta} \geq 1$. Moreover, by (3.13) we derive another restriction that $\delta \leq \alpha$ which indicates that the rate at which individuals discount the future should not exceed the rate of outflow from the stock of migrants.

From (3.10), $S = \frac{v_A}{u_X n_A}$,

In SS, $u_X = -(\alpha\pi S - \bar{F}) = -(\delta S - \bar{F})$

$$v_A = A, \; n_A = \frac{\partial n}{\partial A} = -\frac{\bar{n}}{(A+1)^2}$$

$$A = (\bar{F} - \alpha\pi S)(-\frac{\bar{n}}{(A+1)^2})S$$

$$S = \frac{A}{(\bar{F} - \alpha\pi S)\left(-\frac{\bar{n}}{(A+1)^2}\right)} = \frac{A(A+1)^2}{-\bar{n}\bar{F} + \bar{n}\alpha\pi S}$$

$$\bar{F}S - \alpha\pi S^2 + \frac{(A+1)^2 A}{\bar{n}} = 0 \tag{3.14}$$

$$S_{1,2} = \frac{\bar{F} \pm \sqrt{\bar{F}^2 + 4\alpha\pi\frac{(A+1)^2A}{\bar{n}}}}{2\alpha\pi} \tag{3.15}$$

$$S_{1,2} = \frac{\bar{F} \pm \sqrt{\frac{\bar{F}^2\bar{n}+4\alpha\pi(A+1)^2A}{\bar{n}}}}{2\alpha\pi}$$

$$\text{As } S \geq 0, \text{ then } \bar{F} - \sqrt{\frac{\bar{F}^2\bar{n} + 4\alpha\pi(A+1)^2A}{\bar{n}}} \geq 0$$

$$\bar{F}^2 \geq \frac{\bar{F}^2\bar{n} + 4\alpha\pi(A+1)^2A}{\bar{n}} \quad \rightarrow \quad 0 \geq \alpha\pi(A+1)^2A$$

Only satisfied value is for $A = 0$ which is also included in (3.15) with the plus sign, hence, we discard the minus sign (one of the roots of S^{SS}) from there.

Integrating A^{SS} and π^{SS} into the equation:

$$S = \bar{F} + \sqrt{\bar{F}^2 + 4\delta\bar{n}\frac{(\bar{n}-\delta)}{\delta^3}}$$

$$S^{SS} = \frac{\delta\bar{F} + \sqrt{\delta^2\bar{F}^2 + 4\bar{n}(\bar{n}-\delta)}}{2\delta^2} \tag{3.16}$$

System dynamics:

To find the steady-state or long-run equilibrium values of A, S and π, we set the differential equations for $\dot{A}$, $\dot{S}$ and $\dot{\pi}$ equal to zero. This is because at steady state, the variables do not change over time, and thus their derivatives with respect to time are zero.

The differential equation for S is $\dot{S} = (n - \alpha\pi)S$, and we already used it in 3.13.

To find the $\dot{\pi}$ equation we take the time derivative of the equation of λ:

$$\lambda = F - \alpha\pi S$$
$$\dot{\lambda} = -\alpha\left(S\dot{\pi} + \pi\dot{S}\right)$$
$$\dot{S} = (n - \alpha\pi)S$$

Since drawing three dimensional graph of the variables A, π and S is very complex and not suitable to work on, we can impose the variable A on others, so, we can acquire the graph of π and S which requires us to change the functions dependent on A to another variable (here we can choose S). In the following equations, it can be seen that while n was dependent on A, it's reverted to be dependent on S.

$$\frac{\dot{\lambda}}{\lambda} = \hat{\lambda} = \delta - n(S), \quad \text{by (3.11)}$$

$$\frac{-\alpha(S\dot{\pi} + \pi(n-\alpha\pi)S)}{F - \alpha\pi S} = \delta - n$$

$$\dot{\pi} = -\pi(2n - \alpha\pi - \delta) - \frac{F(\delta - n)}{\alpha S}$$
$$\dot{\pi} = 0 \iff \pi(2n - \alpha\pi - \delta) = \frac{F(n - \delta)}{\alpha S}$$

In steady state, the rate of change of the probability, $\dot{\pi}$, will be zero. The equation above shows which equation should hold for this condition of steady state to be satisfied. This equation should normally help us draw and analyze phase planes, namely nullclines. Because it is complex to understand how it behaves when there is a change in S, we will attempt to leave S to be only variable, so that we can take derivative to understand its behaviour. Therefore, we further get into detail by substituting n and then excluding A.

In the following equations we will substitute n in its original equation (with A) then find the function of A dependent on S. As mentioned above, we try to exclude A from the dynamics.

$$\bar{F}\bar{n} - \bar{F}\delta(A+1) + \delta\alpha\pi S(A+1) - 2\bar{n}\alpha\pi S + \alpha^2\pi^2 S(A+1) = 0$$
$$\bar{F}\bar{n} - \bar{F}\delta A - \delta\bar{F} + \delta\alpha\pi SA + \delta\alpha\pi S - 2\bar{n}\alpha\pi S + \alpha^2\pi^2 SA + \alpha^2\pi^2 S = 0$$

where A in terms of S:

$$A(S) = \frac{1}{3}\left(\left(\frac{27y}{2} + \frac{3}{2}\sqrt{3}\sqrt{y(27y+4)} + 1\right)^{1/3} + \frac{1}{\left(\frac{27y}{2} + \frac{3}{2}\sqrt{3}\sqrt{y(27y+4)} + 1\right)^{1/3}} - 2\right)$$

where $y = \bar{n}S(\alpha\pi S - \bar{F})$

Now, we acquired the equation of π-nullcline in terms of S by leaving out A. Again, to understand the behaviour when there is a shock in S, we can check the sign of change A wrt S:

$$\frac{\partial y}{\partial S} = \bar{n}(2\delta S - \bar{F}) \lesseqgtr 0 \quad \rightarrow \quad 2\delta S \lesseqgtr \bar{F} \quad \rightarrow \quad S \lesseqgtr \frac{\bar{F}}{2\delta}$$

From above derivative and its implications, we can conclude that even if we assume $S > \frac{\bar{F}}{2\delta}$ and get $\frac{\partial A}{\partial S} > 0$, implying $\frac{\partial n}{\partial S} < 0$, still, it is not enough to have an idea of the sign of $\frac{\partial \dot{\pi}}{\partial S}$, only we can get that $\frac{\partial S}{\partial \pi} < 0$, implying $\dot{S} = 0$ will be decreasing in π.

For this nonlinear equation, which became more complex and ambiguous, an explicit analytical solution may not be available. Generally, for given parameter values, it would be a good idea to solve it numerically.

The restrictions applied in the following graph, Figure (3.5), are that as probability cant be over 1, then $\alpha > n$ and as denominator of $\dot{\pi}$ should not have a root between 0 and 1, then $n > (\alpha + \delta)/2$.

After some calibrations, for the following parameters we get the steady states of S and π as drawn in Figure (3.5):

$$\alpha = 0.0025,\ \delta = 0.00005,\ \bar{n} = 0.0018875$$
$$S^{SS} = 819,427 \text{ and } \pi^{SS} = 0.5931$$

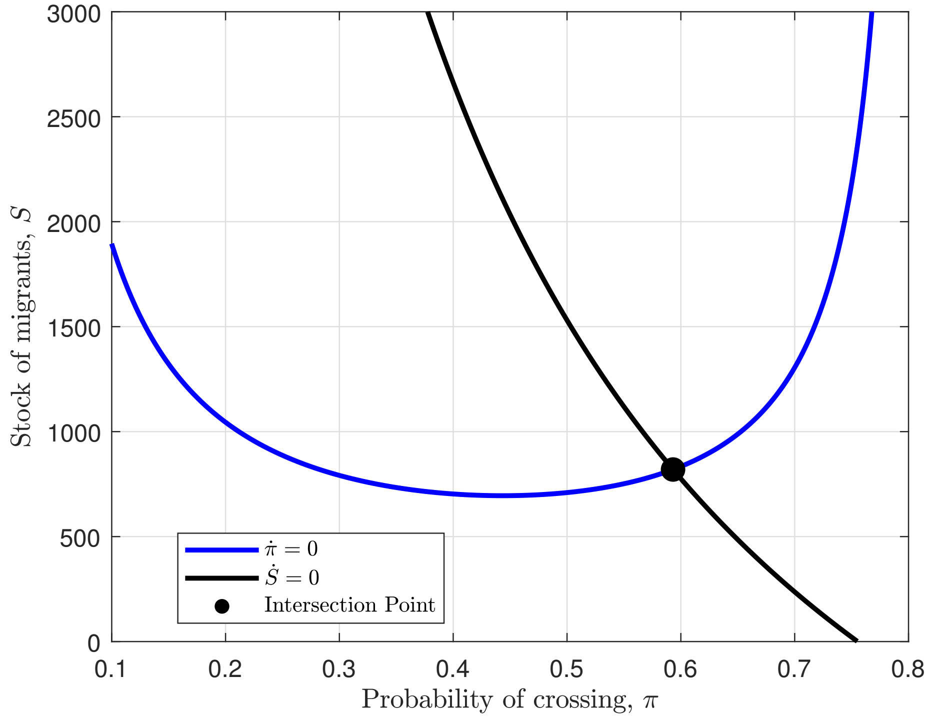


Figure 3.5: Diminishing Returns in Optimal Abatement: Graph of $\dot{\pi}$ and $\dot{S}$

Calculations suggest a wide range of results for abatement, the probability, and the stock after adding abatement to the setup. When we take both probability and stock into account, we can deduce that larger stocks will be found at both ends of the probability spectrum, but in a steady state, the likelihood of crossing the border should be lower when there is more stock. This characteristic highlights the system's dynamic elements. Although abatement has diminished returns in this scenario, it will nevertheless help reduce both the probability and the stock simultaneously.

3.3.2 A Setup with Utility Function and Linear Return of Abatement

Now we can move forward to attempt at solving the system by a little simplification over the rate of inflow into stock of migration function by making the return of abatement not diminishing but linear.

So let's assume the function as $n = \bar{n} - \beta A$; where β is a small coefficient.

With the same assumptions and introduction of the last sub-model other than for $n(A)$, lets state the necessary function and solve the optimal control problem.

$$u(X) = -\frac{1}{2}X^2, \quad X = \alpha\pi S - \bar{F}, \quad v(A) = \frac{A^2}{2}$$
$$\omega(X,A) = u(X) - v(A), \quad n(A) = \bar{n} - \beta A$$

The Hamiltonian function:

$$H = \omega(X,A) + \lambda[(n(A) - \alpha\pi)S]$$
$$H = u(X) - \nu(A) + \lambda[(n(A) - \alpha\pi)S]$$
$$H = -\frac{1}{2}X^2 - \frac{A^2}{2} + \lambda[(\bar{n} - \beta A - \alpha\pi)S]$$

Where:

- Control variable: π and A
- State variable: S
- Co-state: λ

.

Solving the Hamiltonian and not getting into detail of equations that are similar to previous section:

Derivative wrt $\pi: u_X\alpha S - \lambda\alpha S = 0 \rightarrow \lambda = u_X$

Derivative wrt $S: u_X\alpha\pi - \lambda\alpha\pi + \lambda n = \delta\lambda - \dot{\lambda}$

$\lambda n = \delta\lambda - \dot{\lambda} \quad \rightarrow \quad \hat{\lambda} = \delta - n$

In SS, $\hat{\lambda} = 0 \quad \rightarrow \quad n = \delta \quad \rightarrow \quad A^{SS} = \dfrac{\bar{n} - \delta}{\beta}$

Here we find that steady state of A is dependent on δ. A restriction arise from this equation that $\bar{n} \geq \delta$ for a non-negative A value.

$$\text{In SS, } \dot{S} = 0 \rightarrow n = \alpha\pi \quad \rightarrow \quad \pi^{SS} = \frac{\delta}{\alpha} \tag{3.17}$$

Here we find that steady state of π which implies another restriction that $\frac{\delta}{\alpha} \leq 1$, since the maximum value for probability is 1.

Derivative wrt $A: \nu_A = u_X n_A S, \quad u_X = \bar{F} - \alpha\pi S, \quad \nu_A = A, n_A = -\beta$

$$A = (\bar{F} - \alpha\pi S)(-\beta)S = -\bar{F}\beta S + \alpha\pi S^2\beta = \alpha\pi\beta S^2 - \beta\bar{F}S \tag{3.18}$$

By 3.18 and 3.17, $S_{1,2}^{SS} = \dfrac{\bar{F} \pm \sqrt{\frac{4A\delta + \beta\bar{F}^2}{\beta}}}{2\delta}$

Substituting $A^{SS} \rightarrow S_{1,2}^{SS} = \dfrac{\bar{F} \pm \sqrt{\frac{4\frac{(\bar{n}-\delta)}{\beta}\delta + \beta\bar{F}^2}{\beta}}}{2\delta}$

$$S_{1,2}^{SS} = \frac{\beta\bar{F} \pm \sqrt{4\bar{n}\delta - 4\delta^2 + \beta^2\bar{F}^2}}{2\delta\beta}$$

Since $\beta\bar{F} - \sqrt{4\bar{n}\delta - 4\delta^2 + \beta^2\bar{F}^2} < 0$,

then only $S^{SS} = \dfrac{\beta\bar{F} + \sqrt{4\bar{n}\delta - 4\delta^2 + \beta^2\bar{F}^2}}{2\delta\beta}$ can be the root.

System dynamics:

We are following the same procedure as in the previous section. As a reminder, at the steady state, variables remain constant over time. Thus, to determine the steady-state or long-run equilibrium values of A, S, and π, we set the differential equations for $\dot{A}$, $\dot{S}$, and $\dot{\pi}$ to zero.

Notably, we have already utilized the differential equation for S, which is $\dot{S} = (n - \alpha\pi)S$, in 3.17.

Finding curve of $\dot{\pi}$:

$$\lambda = \bar{F} - \alpha\pi S$$
$$\dot{\lambda} = -\alpha\left(S\dot{\pi} + \pi\dot{S}\right) \tag{3.19}$$
$$\dot{S} = (n - \alpha\pi)S$$

Substituting $\dot{S} \quad \rightarrow \quad \dot{\lambda} = -\alpha(S\dot{\pi} + \pi(n - \alpha\pi)S) = -\alpha S(\dot{\pi} + \pi(n - \alpha\pi))$

$$\frac{\dot{\lambda}}{\lambda} = \hat{\lambda} = \delta - n(A) \tag{3.20}$$

Taking (3.18) and inserting into (3.20):

$$A = \beta S(\alpha\pi S - \bar{F})$$

$$\dot{\lambda} = (\bar{F} - \alpha\pi S)\left(\delta - \bar{n} + \beta^2 S(\alpha\pi S - \bar{F})\right)$$

Substitute for $\dot{\lambda}$ from (3.19):

$$-\alpha S(\dot{\pi} + \pi(n - \alpha\pi)) = (\bar{F} - \alpha\pi S)(\delta - \bar{n}) - \beta^2 S(\alpha\pi S - \bar{F})^2$$

Substitute n in LHS:

$$-\alpha S\dot{\pi} - \alpha S\pi(\bar{n} - \beta A - \alpha\pi) = (\bar{F} - \alpha\pi S)(\delta - \bar{n}) - \beta^2 S(\alpha\pi S - \bar{F})^2$$

$$-\alpha S\dot{\pi} - \alpha S\pi\left(\bar{n} - \beta^2(\alpha\pi S - \bar{F})S - \alpha\pi\right) = (\bar{F} - \alpha\pi S)(\delta - \bar{n}) - \beta^2 S(\alpha\pi S - \bar{F})^2$$

$$\Rightarrow \dot{\pi} = \left(-\frac{1}{\alpha S}\right)\left\{(\bar{F} - \alpha\pi S)(\delta - \bar{n}) - \beta^2 S\left(\alpha\pi S - \bar{F}\right)^2 + \alpha S\pi\left[\bar{n} - \alpha\pi - \beta^2 S(\alpha\pi S - \bar{F})\right]\right\}$$

$$= \left(-\frac{1}{\alpha S}\right)\left\{(\bar{F} - \alpha\pi S)(\delta - \bar{n}) - \beta^2 S(\alpha\pi S - \bar{F})^2\right\} - \pi\left[\bar{n} - \alpha\pi - \beta^2 S(\alpha\pi S - \bar{F})\right]$$

$$= \frac{(\bar{n}-\delta)(\bar{F}-\alpha\pi S)}{\alpha S} + \frac{\beta^2(\alpha\pi S-\bar{F})^2}{\alpha} - \pi\bar{n} + \alpha\pi^2 + \beta^2\pi S(\alpha\pi S-\bar{F})$$

$$= \frac{(\bar{n}-\delta)\bar{F}}{\alpha S} - \frac{(\bar{n}-\delta)\pi\alpha S}{\alpha S} + \frac{\beta^2(\alpha\pi S-\bar{F})^2}{\alpha} - \pi\bar{n} + \alpha\pi^2 + \beta^2\alpha(\pi S)^2 - \beta^2\pi S\bar{F}$$

$$= \frac{(\bar{n}-\delta)\bar{F}}{\alpha S} - \bar{n}\pi + \pi\delta + \beta^2\left((\alpha\pi S)^2 - 2\alpha\pi S\bar{F} + \bar{F}^2\right) - \pi\bar{n} + \alpha\pi^2 + \beta^2\alpha(\pi S)^2 - \beta^2\pi S\bar{F}$$

$$\dot{\pi} = \frac{(\bar{n}-\delta)\bar{F}}{\alpha S} - 2\pi\bar{n} + \pi\delta + \alpha\pi^2 + 2\beta^2(\pi S)^2\alpha - 3\beta^2\pi S\bar{F} + \frac{\beta^2}{\alpha}\bar{F}$$

As we found $\dot{\pi}$, we can draw the curve of $\dot{\pi} = 0$. We can do this by solving $S(\pi)|_{\dot{\pi}=0}$ numerically.

Finding curve of $\dot{S} = 0$

$$\dot{S} = (\bar{n} - \beta A - \alpha\pi)S$$

$$\dot{S} = 0 \Leftrightarrow \bar{n} - \beta A - \alpha\pi = 0$$

$$\bar{n} - \beta^2 S(\alpha\pi S - \bar{F}) - \alpha\pi = 0$$

$$\bar{n} - \beta^2 S^2\alpha\pi + \beta^2 S\bar{F} - \alpha\pi = 0$$

$$-\beta^2 S^2\alpha\pi + \beta^2 S\bar{F} + \bar{n} - \alpha\pi = 0 \;|: \beta^2$$

$$-\alpha\pi S^2 + \bar{F}S + \frac{\bar{n}-\alpha\pi}{\beta^2} = 0, S \geqslant 0$$

$$S_{1,2} = \frac{-\bar{F} \pm \sqrt{\bar{F}^2 + 4\alpha\pi\frac{\bar{n}-\alpha\pi}{\beta^2}}}{-2\alpha\pi} = \frac{\bar{F} \mp \sqrt{\bar{F}^2 + 4\alpha\pi\frac{\bar{n}-\alpha\pi}{\beta^2}}}{2\alpha\pi}$$

Around SS $\alpha\pi \cong \delta \Rightarrow \bar{n} - \alpha\pi \geqslant 0$

$\Rightarrow \sqrt{\bar{F}^2 + 4\alpha\pi\frac{\bar{n}-\alpha\pi}{\beta^2}} > \bar{F} \Rightarrow$ only $S = \frac{\bar{F} + \sqrt{\bar{F}^2 + 4\alpha\pi\frac{\bar{n}-\alpha\pi}{\beta^2}}}{2\alpha\pi}$ can be possible.

$$S = \frac{\bar{F}}{2\alpha\pi} + \frac{1}{2\alpha\pi}\sqrt{\bar{F}^2 + 4\alpha\pi\frac{\bar{n}-\alpha\pi}{\beta^2}}$$

Around SS $\quad\rightarrow\quad S = \frac{\bar{F}}{\alpha\pi}$ which is a hyperbola.

Here a restriction can be set for $\bar{n}$ that cannot be larger than α, it's because:

$$\dot{S} = 0 \rightarrow (n - \alpha\pi)S = 0$$

$$\text{As } S \neq 0, \quad \pi = \frac{n}{\alpha} = \frac{\bar{n} + \beta^2 S(\bar{F} - \alpha\pi S)}{\alpha}$$

$$\bar{n} \gg \beta^2 S(\bar{F} - \alpha\pi S) \quad \rightarrow \quad \pi \approx \frac{\bar{n}}{\alpha} \leqslant 1$$

Another note is that from (3.18) it can be derived that A can be only positive when:

$$\alpha\pi S - \bar{F} \geq 0$$

leaving variables on LHS:

$$\pi S \geq \frac{\bar{F}}{\alpha}.$$

So, this condition implies A is not necessarily positive.

After numerical solutions, we can draw the graph, Figure (3.6):

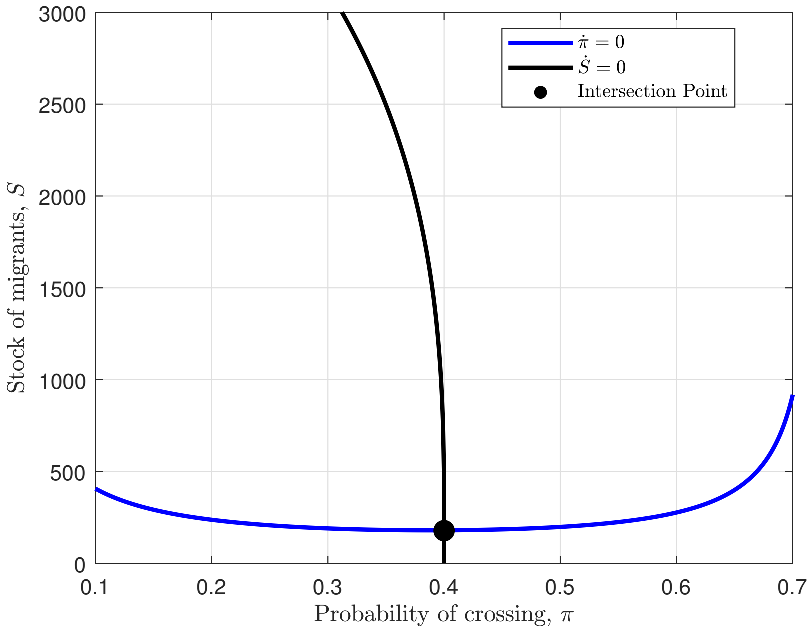


Figure 3.6: Linear Return in Optimal Abatement: Graph of $\dot{\pi}$ and $\dot{S}$

After some calibrations, for the following parameters we get the steady state S and π as shown in (3.6):

$$\alpha = 0.0125,\ \delta = 0.000001,\ \bar{n} = 0.005,\ \beta = 0.0001$$
$$S^{SS} = 180,241 \text{ and } \pi^{SS} = 0.4$$

To figure out the dynamics it is necessary to understand the behaviour of $\dot{\pi}$ for a change in S, relationship of $\dot{\pi}$ equation we found above to S was complex. As we did last time lets take the derivative of it wrt S:

$$\frac{d}{dS}\left(\dot{\pi} = \frac{(\bar{n}-\delta)\bar{F}}{\alpha S} - 2\pi\bar{n} + \pi\delta + \alpha\pi^2 + 2\beta^2(\pi S)^2\alpha - 3\beta^2\pi S\bar{F} + \frac{\beta^2}{\alpha}\bar{F}\right)$$

$$= 4\alpha\beta^2 S\pi^2 + \frac{\bar{F}(\delta-\bar{n})}{\alpha S^2} - 3\beta^2\bar{F}\pi$$

Whether this complex equation is negative or positive is still ambiguous. Let's try to figure out numerically the behaviour of $\dot{\pi}$ in the presence of a shock in S. $\dot{\pi}$ curve splits the graph into two regions: above and below. We choose any value of π and compute the derivative for two different values of S, corresponding to above and below the $\dot{\pi} = 0$ curve. Let's take $\pi = 0.5$ and $S = 1500$ for above and $S = 50$ for below. We can find a result via substituting parameters in their place. After calculations, the sign of $\dot{\pi}$ is negative when $S = 50$, and for $S = 1500$ it is positive. With this information we can sketch the phase planes and it shows that we have a stable system in the face of shocks.

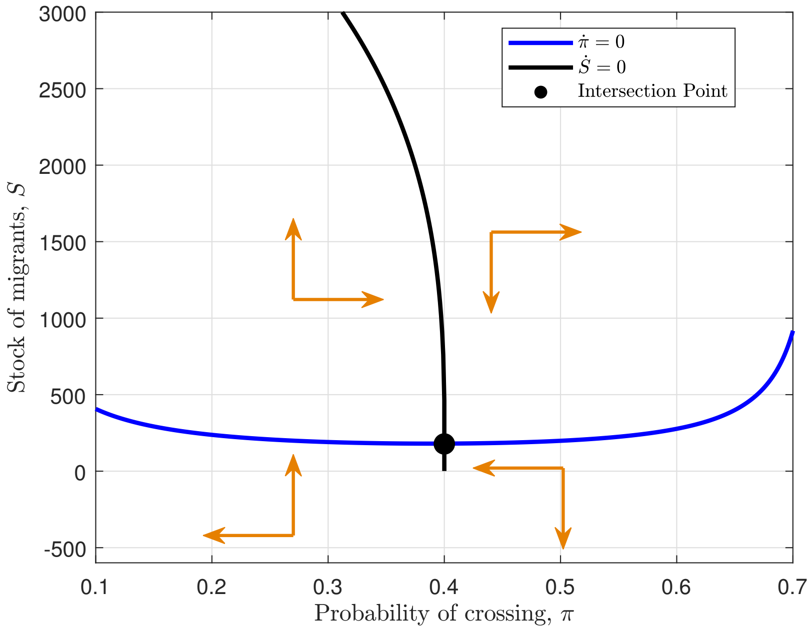


Figure 3.7: Linear Return in Optimal Abatement: Schedule of Dynamics

In this configuration, while abatement has no diminishing returns but linear, the calculations indicate results akin to those with diminishing effects. As distance from steady-state probabilities increases, there will be larger stocks of migrants. Concurrently, an increase in the stock results in a decrease in the steady-state probability. It's worth noting that these results incorporate varying abatement.

Fixing A

Let's make things a bit more easier. Let's fix A at some value, say $\tilde{A}$, which implies that n is fixed at $\tilde{n} = \bar{n} - \beta\tilde{A}$ so we get $\dot{S} = (\tilde{n} - \alpha\pi)S$. The problem here is where to fix A.

Let's state the necessary function and solve the optimal control problem:

$$u(X) = -\frac{1}{2}X^2, \quad X = \alpha\pi S - \bar{F}, \quad v(\tilde{A}) = \frac{\tilde{A}^2}{2} \tag{3.21}$$

$$\omega(X, \tilde{A}) = u(X) - v(\tilde{A}), \quad n(\tilde{A}) = \bar{n} - \beta\tilde{A} \tag{3.22}$$

The Hamiltonian function:

$$H = \omega(X, \tilde{A}) + \lambda[(n(\tilde{A}) - \alpha\pi)S] \tag{3.23}$$

$$H = -\frac{1}{2}X^2 - \frac{\tilde{A}^2}{2} + \lambda[(\bar{n} - \beta\tilde{A} - \alpha\pi)S] \tag{3.24}$$

Where

- Control variable: π
- State variable: S
- Co-state: λ

Let's solve the Hamiltonian:

$$\begin{aligned}
&\lambda : \dot{S} = (\bar{n} - \beta\tilde{A} - \alpha\pi)S \\
&\pi : -\alpha S(\alpha\pi S - \bar{F}) - \lambda\alpha S = 0 \quad \rightarrow \quad \lambda = u_X \\
&S : -\alpha\pi(\alpha\pi S - \bar{F}) + \lambda(\tilde{n} - \alpha\pi) = \delta\lambda - \dot{\lambda} | : \lambda \\
&\quad \alpha\pi + (\tilde{n} - \alpha\pi) = \delta - \hat{\lambda} \quad \rightarrow \quad \tilde{n} = \delta - \hat{\lambda} \quad \rightarrow \quad \hat{\lambda} = \delta - \tilde{n}
\end{aligned}$$

In Steady State:

- $\hat{\lambda} = 0$ which implies $\tilde{n}^{SS} = \delta$, then $\bar{n} - \beta\tilde{A} = \delta \quad \rightarrow \quad \tilde{A}^{SS} = \frac{\bar{n}-\delta}{\beta}$ and
- $\dot{S} = 0$ which implies $\tilde{n} - \alpha\pi = 0$, then $\pi^{SS} = \frac{\bar{n}-\beta\tilde{A}}{\alpha}$.

System dynamics:
Taking the derivative of λ with respect to time:

$$\dot{\lambda} = -(\alpha\pi\dot{S} + \alpha\dot{\pi}S), \text{ by substiuting } \dot{S} \tag{3.25}$$

$$\dot{\lambda} = -(\alpha\pi(\tilde{n} - \alpha\pi)S + \alpha\dot{\pi}S), | : \lambda = u_X$$

$$\frac{\dot{\lambda}}{\lambda} = \frac{-(\alpha\pi(\tilde{n} - \alpha\pi)S + \alpha\dot{\pi}S)}{\bar{F} - \alpha\pi S}$$

$$\dot{\pi} = \frac{\bar{F}(\tilde{n} - \delta)}{\alpha S} - \pi(2\tilde{n} - \alpha\pi - \delta) \tag{3.26}$$

Now let's derive the schedules $\dot{S} = 0$ and $\dot{\pi} = 0$.
As we solved:
$\dot{S} = (\tilde{n} - \alpha\pi)S$ implied $\pi^{SS} = \frac{\bar{n}-\beta\tilde{A}}{\alpha}$.
And for $\dot{\pi} = 0$:

$$\begin{aligned}
&\dot{\pi} = \frac{\bar{F}(\tilde{n} - \delta)}{\alpha S} - \pi(2\tilde{n} - \alpha\pi - \delta) = 0 \\
&\bar{F}(\tilde{n} - \delta) = \alpha\pi S(2\tilde{n} - \alpha\pi - \delta) \\
&S^{SS} = \frac{\bar{F}(\tilde{n} - \delta)}{\alpha\pi(2\tilde{n} - \alpha\pi - \delta)}
\end{aligned}$$

Now we can solve this non-linear equation numerically for given parameter values. After some calibrations, for the following parameters we get the steady state S and π as displayed in Figure 3.9:

$$\alpha = 0.01,\ \delta = 0.0001,\ \tilde{n} = 0.00404,\ \beta = 0.0002,\ \tilde{A} = 200.2,\ n = 0.004$$
$$S^{SS} = 222,660 \text{ and } \pi^{SS} = 0.4$$

As we draw the $\dot{\pi}$ and $\dot{S}$ in the graph we get two lines intersecting at Intersection Point. The lines split the graph area into four regions.

To determine the dynamics in each region, we need to observe how S and π behave in each region. We will represent their behaviour with arrows showing in which direction the variables move in each region. So, we take the derivative of $\dot{\pi}$ wrt S to understand the behaviour of the system under shocks:

$$\frac{\partial \dot{\pi}}{\partial S} = -\frac{(\tilde{n}-\delta)\bar{F}}{\alpha S^2} \lesseqgtr 0 \iff \tilde{n}-\delta \lesseqgtr 0 \tag{3.27}$$

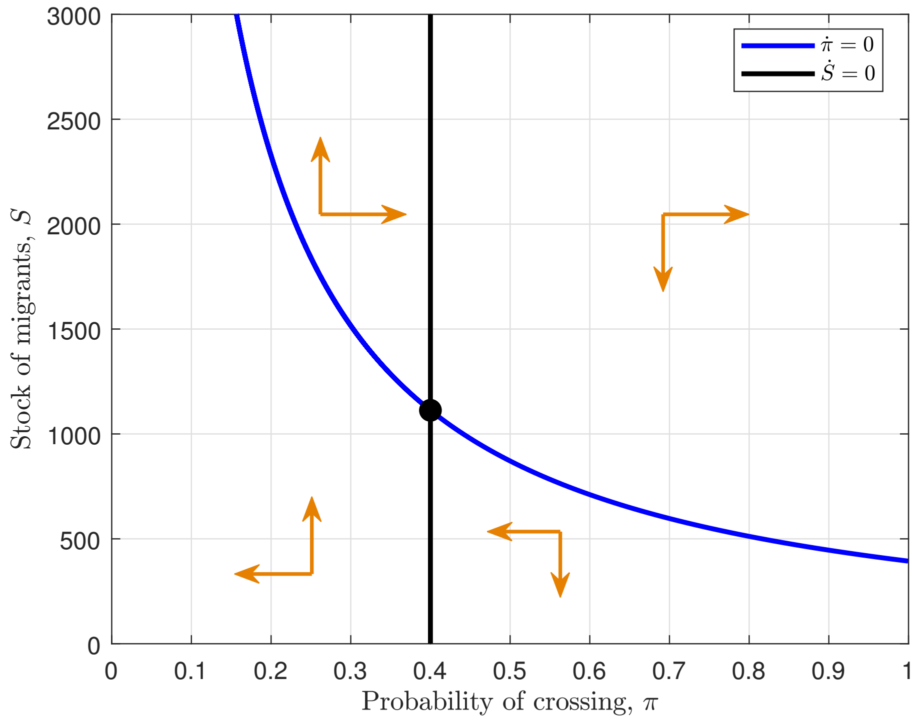


Figure 3.8: Fixed Abatement: Dynamics of $\dot{\pi}$ and $\dot{S}$ when $\delta > n$.

If $\delta > n$, then after a shock, schedules doesn't converge to steady state, represented in Figure 3.8, meaning that the system is unstable. This result implies that the Host country discount the future heavily, perhaps because it prioritizes the present. If it's the case, shocks in such a system could lead to erratic behavior, with no convergence to a stable state.

When $n > \delta$ then schedules constitute a saddle point, implied by dashed line in Figure 3.9, making

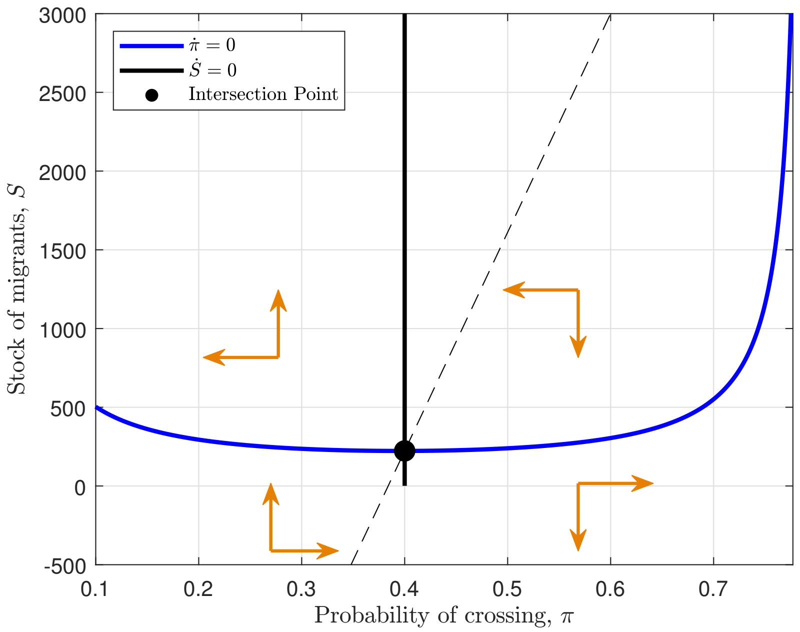


Figure 3.9: Fixed Abatement: Dynamics of $\dot{\pi}$ and $\dot{S}$ when $n > \delta$.

it possible to converge to steady state. A saddle point is a type of equilibrium in which trajectories of the system approach the steady state along one dimension and diverge along another. This means that there is a unique path (the stable manifold of the saddle) that will lead the system to the steady state. If the system is lands on this path, it will converge to the steady state. However, if it strays from this path, it will diverge away from the equilibrium. Thus, while the system can be stable, it is conditionally stable, requiring specific conditions for convergence. Hence, this system can be stable.

In this setup, having abatement a constant, fixes the rate of the inflow of migrants into the stock. When $n > \delta$, there will be higher stocks of migrants at both low and high probabilities and the steady state probability will be fixed. The curves depicted in the graph highly depended on the level of climate finance, denoted as $\tilde{A}$. An increased commitment to climate finance will lead to a reduced inflow into the migrant stock and diminishing both the steady states of the stock and the probability of border-crossing.

An Adjustment Attempt in the Utility Function

As seen from the graphs, the asymptote of $\dot{\pi} = 0$ function passes for values $\pi < 1$. We can try to adjust the utility function in the following way to have an asymptote at $\pi = 1$ which implies while the probability of crossing approaches to 1 the stock of migrants will approach to its maximum:
$u(X) = -\frac{1}{2}X^2, \quad X = \alpha\pi S - \bar{F} + (\alpha + \delta - 2n)S$, keeping everything else the same, let's summarize the calculations:

$$v(\tilde{A}) = \frac{\tilde{A}^2}{2}$$
$$\omega(X, \tilde{A}) = u(X) - v(\tilde{A}), \quad n(\tilde{A}) = \bar{n} - \beta\tilde{A}$$

The Hamiltonian function:

$$H = \omega(X,\tilde{A}) + \lambda[(n(\tilde{A}) - \alpha\pi)S]$$
$$H = -\frac{1}{2}X^2 - \frac{\tilde{A}^2}{2} + \lambda[(\bar{n} - \beta\tilde{A} - \alpha\pi)S]$$

Where

- Control variable: π
- State variable: S
- Co-state: λ

Solving the Hamiltonian:

$$\pi : \lambda = u_X = F - \alpha S(\pi + \alpha + \delta - 2\tilde{n})$$
$$S : \tilde{n} + (\alpha + \delta - 2\tilde{n}) = \delta - \hat{\lambda} \quad \rightarrow \quad \hat{\lambda} = \tilde{n} - \alpha$$

$$\dot{S} = (\tilde{n} - \alpha\pi)S$$

In Steady State:

- $\hat{\lambda} = 0$ which implies $\tilde{n}^{SS} = \alpha$, then $\bar{n} - \beta\tilde{A} = \alpha$ and
- $\dot{S} = 0$ which implies $\tilde{n} - \alpha\pi = 0$, then $\pi^{SS} = \frac{\bar{n}-\beta\tilde{A}}{\alpha}$.

System dynamics:

$$\dot{\lambda} = -\dot{S}(\alpha\pi + \alpha + \delta - 2\tilde{n}) - \dot{\pi}(\alpha S), \text{ by substiuting } \dot{S}$$
$$\dot{\pi} = \frac{\bar{F}(\alpha - \tilde{n})}{\alpha S} + (1 - \pi)(2\tilde{n} - \alpha - \delta - \alpha\pi)$$

In steady state $\dot{\pi} = 0$ then we have:

$$S^{SS} = \frac{\bar{F}(\alpha - \tilde{n})}{\alpha(\alpha\pi + \alpha + \delta - 2\tilde{n})(1 - \pi)}$$

In terms of shocks, $\dot{S}$ will decrease when π increase. On the other hand for $\dot{\pi}$ we can check the derivative of it wrt S:

$$\frac{\partial\dot{\pi}}{\partial S} = -\frac{(\alpha - \tilde{n})\bar{F}}{\alpha S^2} \lesseqgtr 0 \iff \alpha - \tilde{n} \lesseqgtr 0$$

Since we have $\alpha > \tilde{n}$ always as restriction, then $\frac{\partial\dot{\pi}}{\partial S}$ will be negative implying for an increase in S, $\dot{\pi}$ will decrease.

As we have the equations for $\dot{\pi} = 0$ and $\dot{S} = 0$,and we understand their behaviour, we can draw the steady state curves, inspect the schedules and decide on stability.

After some calibrations, for the following parameters we get the steady state S and π as shown in Figure (3.10):

$$\alpha = 0.0025,\ \delta = 0.00001,\ \bar{n} = 0.02077,\ \beta = 0.1,\ \tilde{A} = 200.2,\ n = 0.00075$$
$$S^{SS} = 505,678 \text{ and } \pi^{SS} = 0.3$$

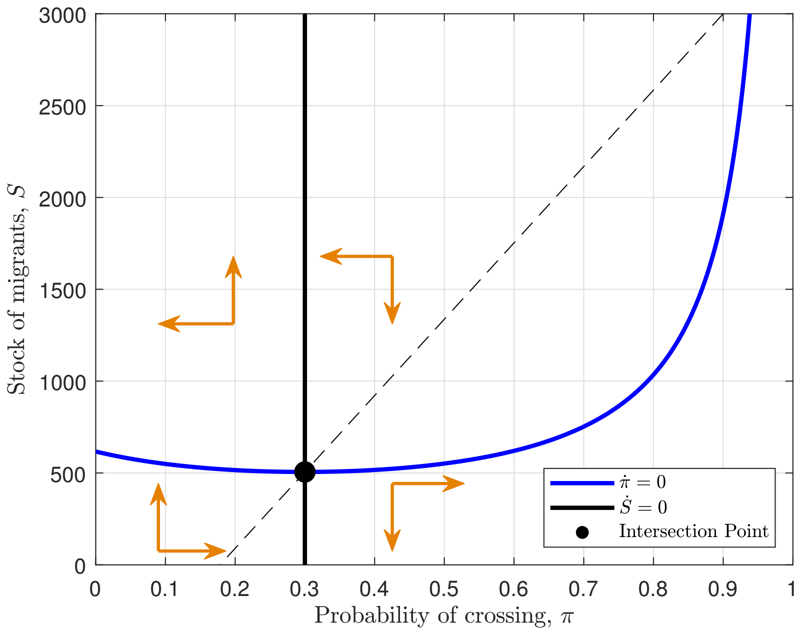


Figure 3.10: Fixed Abatement and Adjusted Utility: Dynamics of $\dot{\pi}$ and $\dot{S}$

As illustrated in the graph, Figure (3.10), schedules constitute a saddle point where there is a possibility to converge to steady state.

This extension section of the Model 3.2 deduces if there would be higher disutility from excessive migration, over the threshold $\bar{F}$, same level of the stock compared to lower disutility can be only achieved in higher levels of probabilities. In other words, when Host country has elevated preference of not having excess migration will trigger coping tools that result in lower stocks of migrants.

The policy implications of this configuration is similar to the preceding models with saddle points, implying utmost care should be put into the policy making process in times of shocks to stabilize the migration situation.

Chapter 4

Discussion

Comparative Analysis of Models on Climate and Migration

This thesis presents a series of models inspired by Brausmann and Djajić (2022), that highlight the importance of abatement in shaping migration due to climate change. At the core is the role of climate finance. If used effectively, it can reduce the main reasons causing people to migrate from their home countries. Specifically, it can improve the climate situation and reduce the number of people forced to move because of environmental reasons. Each model presents a different perspective on this relationship, giving us a deeper understanding of the connection between climate finance and migration.

Model 1: Climate as a Reason for Migration The first model integrates the climate factor based on Brausmann and Djajić's (2022) foundational work. It shows that by using abatement (or climate improvement measures), we can reduce the need for people to migrate. However, abatement cuts funds allocated for spending on border control. So, there's a balance to consider: improving conditions in Source country could help loosen border controls in Host country.

Model 2: Budgeting for Climate and Borders The second model continues with the idea of abatement but adds a budget constraint. It looks at how Host country, with a set budget, can decide the best way to spend between improving the climate (abatement) of Source country and controlling their borders. This helps us understand the economic choices countries face when dealing with climate migration.

Model 3: Measuring Benefits and Finding the Best Approach Our third model differed with its inclusion of utility functions, hence enabling us to assess optimality in our setups. We start with a setup to include pollution reduction efforts (abatement), enabling us to find steady state of the system and hence to check the stability of the system. In the last part, a fixed abatement enables us to sketch better phase planes and stability interpretation, which shows the importance of consistent efforts to reduce pollution and its effects on migration patterns.

From these models, a clear theme emerges: addressing migration caused by climate change is complex. It requires understanding and balancing environmental, economic, and political factors. Hence, results arising from these models should be cautiously approached.

Contribution to the Understanding of Climate Change and Migration

The first model starts with an original thought experiment, challenging conventional approaches to migration control. It examines a paradigm shift, suggesting that perhaps reallocating a portion of funds designated for border control to enhance the living conditions in the migrants' home countries might be more effective in reducing migration. This perspective encourages a proactive stance, aiming to address one of the root causes of migration intensified by climate change, rather than simply reinforcing borders.

Our second model investigates a more complex economic problem. Given a specified budget – using Frontex as a reference point – it handles the optimal allocation of these funds, fortifying borders and aiding the source countries. By revealing this balance, we get a clearer understanding of the trade-offs nations face in the existence of climate related migration.

Lastly, the third model constructs preferences of the Host country, expressed through a utility function, considering scale of migration and budget allocated for climate finance. In this model the principle of diminishing returns is also discussed. Throughout this thesis while environmental migrants are being subject, the mentioned limited number of factors and concepts revolving around them are handled.

Policy Recommendations

Across the three analytical models presented, several significant implications arise about the interplay between climate change and migration. Firstly, there is a clear mutual benefit for both host and source countries when abatement measures are prioritized in the source nations, effectively countering the push factors of migration. Furthermore, while abatement's immediate costs might seem high compared to border control, the long-term reduced migration pressure can provide offsetting savings. The dynamics of migration suggest that strategies should address both the influx rate of potential migrants and the existing stock, while also recognizing the diminishing effects of abatement.

Given these insights, several policy recommendations can be formulated. International stakeholders, particularly potential host countries, should focus on investments in abatement within source nations, leveraging methods like financial aid, technology transfer, or joint environmental projects. Budgetary allocations should balance the short-term needs of border control with the long-term benefits of environmental interventions. Policies should appeal to the complex dynamics of migration, potentially influencing migration decisions. Lastly, efforts should be directed towards improving the quality of life in source countries, positioning environmental initiatives as holistic approaches to improve living standards, addressing both environmental and social drivers of migration.

Chapter 5

Conclusion

Summary of Key Findings

Model One: Climate-Related Conflicts and Migration Mitigation Strategies

The analysis presented via the first model indicates a mutual beneficial trajectory. When host countries increase their abatement measures, even if it necessitates a reduction in border control expenditures, a dual advantage emerges. Specifically, both the migrant population and enforcement spending exhibit a decreasing trend.

Model Two: Budgetary Constraints and Policy Decisions

By reformulating the first model to include budget constraint, we deduce that, for a specified budget, an optimal allocation can be determined between abatement and border control. Graphical representations indicate that investing in efforts to reduce environmental degradation in the Source country reduces both border control expenditures and the stock of migrants.

The numbers imply a higher steady state would be acquired for a lower budget, implying that decreasing the border enforcement spending via abatement is costly. It can be said in this setup, effectiveness of abatement in reducing border control expenses is relatively low. Obviously, there is no one-to-one transition of efficiency from border control spending to abatement. Considering the effect of climate change on migration in the future, this implication of effectiveness is questionable.

Model Three: Dynamics of Migration and Abatement Measures

3.1 Effects of Abatement on Migration Decisions

Introducing abatement effecting both Host country in terms of utility and Source country in terms of migration decisions, calculations imply a broad range of results in three-dimension, abatement, probability of crossing and stock of migrants being each dimension. Taking the probability and the stock into consideration, we can infer that for both ends of probability spectrum, there will be higher stocks, and the steady state probability of passing the border will decrease in increasing stock. This property highlights the dynamic features of the system. Moreover, abatement will help decrease the probability and the stock at the same time, even though abatement has diminishing effects in Source country.

3.2 Abatement and Migrant Dynamics

In this setup, while abatement has no diminishing effects calculations suggest similar results with diminishing effects. Namely, there will be higher stocks of migrants for low and high probabilities and the probability is decreasing with the increasing stock. These results consider a varying climate finance level. If we consider a fixed abatement that Host country pledge to, then we simplify the setup into the scenario that didn't include abatement, having the similar results in different levels depending on the magnitude of abatement. An additional aspect, covered as an extension section of this setup, suggests same level of the stock can be only achieved in higher levels of probabilities in the existence increased disutility from excess migration.

Theoretical Contributions

Theoretical contributions of this research emerge as a bridge between climate change economics and migration studies. Traditionally, both domains have been treated with distinct lenses, and this study adds another brick into the current and contemporary integrated approach in academia.

First and foremost, this research reviews the existing knowledge by identifying the tangible impacts of climate-related drives on migration. Previous studies have emphasized both the direct and indirect consequences of environmental degradation. This research showcases how host countries, when strategically investing in mitigation strategies, can create a win-win scenario, thereby challenging the trade-off between environmental and border control spendings.

Furthermore, by introducing the concept of budgetary constraints, this research adds depth to policy decision-making considerations. It describes the subtle difficulties nations face when navigating the allocation of scarce resources between climate mitigation and border management. This is particularly related to today's global economic climate, where countries struggle with limited budgets but ever-increasing demands. The model serves as a tool for policymakers, offering a comprehensive view of how the effectiveness of abatement measures can vary, especially in relation to border control efforts.

The third model's exploration of the dynamics of migration when considering Host country preferences fills a gap in the literature. This study reveals how the inflow rates of migrants, coupled with a Host country's future discount rate, determine the stability of the migration system. Such insights are helpful for countries aiming to develop predictive migration models, especially in the setting of rapidly changing environmental circumstances.

Additionally, the research contributes to the understanding of the impacts of abatement measures. By delving into both the direct and indirect effects on migration decisions and patterns, it provides a layered perspective on how abatement initiatives can shape future migration trends. Especially notable is the finding that abatement's diminishing returns in the Source country impose a more detailed approach to environmental investment decisions.

In essence, this master's thesis stands as a beacon for scholars and policy-makers alike, providing a holistic understanding of the intersection between climate change and migration. Through its innovative models and findings, it redefines the theoretical landscape, encouraging a more collaborative and integrated approach to tackling one of the most pressing challenges of our time.

Potential Future Research Directions

The models outlined in this thesis offer innovative perspectives on migration dynamics, however, there exist limitations that pave the way for potential refinements and deeper explorations. One prominent limitation across the models is their portrayal of migration as a singular, unidirectional flow. Once migrants are added into the stock, the models assume a state of permanence until successful migration is achieved. In principle, the models primarily capture the phenomena of forced migration. However, it's crucial to recognize that many migrants may opt for reverse migration, returning to their source countries for numerous reasons. Despite this shortcoming, the flexibility of the models is noteworthy; they could be adapted to capture this reverse flow by tweaking the rate of change equation of the stock.

Furthermore, the emphasis within these models predominantly resides on climate change as the primary catalyst for migration, sidelining other pivotal push factors that significantly impact global migration trends. Real-world migration is influenced by a confluence of factors, including but not limited to, conflicts, political instability, persecutions, and economic disparities. Broadening the models to incorporate these diverse motivators would undoubtedly boost their explanatory and predictive capacities.

Moreover, the initial two models excel at establishing steady states but don't encapsulate optimality, suggesting that future studies could benefit from probing into optimal conditions and results to foster a deeper understanding of migration interactions.

Within the specifics, the third model underscores the utility derived solely by the Host country, thereby neglecting the narrative surrounding the Source country's socio-economic dynamics and motivations. Such exclusions limit a holistic understanding of the migration framework. Moreover, while the model takes abatement costs into account, it overlooks the implications of expenditures on border control, which play an influential role in migration dynamics.

It's equally essential to acknowledge the absence of the diaspora's role in our models, especially when its significance is highlighted in the "Dynamics of Mass Migration." Diaspora communities play a pivotal role in facilitating migration by acting as bridges between the Source and Host countries. Their established networks in host countries often provide crucial support to new migrants, offering assistance in finding employment, housing, and navigating unfamiliar cultural landscapes. Additionally, diasporas can influence policy-making in both Host and Source nations, advocating for more migrant-friendly policies. The presence of a strong diaspora in a destination country can also serve as a pull factor, encouraging more individuals from the Source country to migrate, knowing they will have a supportive community upon arrival. Hence, an exploration into diaspora dynamics would undeniably contribute to a richer understanding of global migration patterns, especially in the era of climate change.

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