N° TSE-663

June 2016

"The role of conflict for optimal climate and immigration policy"

Fabien Prieur and Ingmar Schumacher

Toulouse School of Economics

The role of conflict for optimal climate and immigration policy

Fabien Prieur* Ingmar Schumacher†

May 2016

Abstract

In this article we investigate the role that internal and external conflict plays for optimal climate and immigration policy. Reviewing the empirical literature, we put forward five theses regarding the link between climate change, migration, and conflict. Based on these theses, we then develop a theoretical model in which we take the perspective of the North who unilaterally chooses the number of immigrants from a pool of potential migrants that is endogenously determined by the extent of climate change. Accepting these migrants allows increases in local production which not only increases climate change but also gives rise to internal conflicts. In addition, those potential migrants that want to move due to climate change but that are not allowed to immigrate may induce external conflict. While we show that the external and internal conflict play a significant yet decisively different role, it is the co-existence of both conflicts that makes policy making difficult. Considering only one conflict induces significant immigration but no mitigation. Allowing for both types of conflict, then depending on parameters, either a steady state without immigration but with mitigation will be optimal, or a steady state with a larger number of immigrants but less mitigation. Furthermore, we find the possibility of Skiba points, signaling that optimal policy depends on initial conditions, too. During transition we examine the substitutability and complementarity between the mitigation and immigration policy.

Keywords: climate change, immigration, conflict, mitigation.
JEL classification: Q54, Q56, F22.

---

[*] Toulouse School of Economics, Université Toulouse Capitole (INRA), 21, Allée de Brienne 31000, Toulouse, France. E-mail: prieur@supagro.inra.fr

[†] IPAG Business School, 184 boulevard Saint-Germain, 75006 Paris, France, and Department of Economics, Ecole Polytechnique Paris, France. Tel.: +352 621264575. E-mail: ingmar.schumacher@ipag.fr.

1 Introduction

It is now not anymore a question of whether climate change may seriously impact mankind. Instead, the important questions researchers nowadays face are inhowfar we can potentially reduce the extent of climate change on the one hand, and cope with the impact of climate change on the other (Parry 2007). While the former issue relates to the optimal mitigation policies, the latter demands us to understand more clearly the array of options available to especially those that are hit the hardest. There is now mounting evidence that climate change is going to have the strongest impact in the poorer South, with migration being often the only possible choice left (Pachauri et al. 2014). While one may argue that countries should allow immigration for humanitarian reasons (Risse 2008), history has shown that immigration policies tend to framed on economic grounds. What tends to be often forgotten, though, is that large-scale migration may also be breeding ground for conflicts, both inside and outside of recipient countries (Hsiang et al. 2013).[1] As far as we are aware a unified framework that studies the links between conflict, climate change and immigration policy in a dynamic framework is missing. Thus, we here set out to develop one suitable approach by investigating inhowfar a country or region may want to optimally trade-off mitigation and immigration policies when economic and conflict-reducing incentives play a role. The questions that we attempt to answer with this framework are, among others: How would an immigration policy interact with a climate policy? When would the North have an incentive to cut its carbon emissions given the threat of conflict? When are immigration and mitigation policies substitutes or complements? May the current status quo also be important for the optimal policy?

The economic literature on optimal mitigation and climate change is now large and has studied a variety of aspects, mostly emphasizing the role that climate change plays as an externality and then determining the social cost of carbon to internalize this externality (Stern 2007, Nordhaus 2014a, Nordhaus 2014b, Golosov et al. 2014, Ploeg and Withagen 2014). However, even regional models of climate change (Nordhaus and Yang 1996, Tol 1997, Peck and TJ 1999, Manne and Richels 2005, Bosetti et al. 2006) have, as of now, avoided to investigate the role that climate-driven migration plays for climate policy (McLeman 2013). There exist only few

---

[1] As United Nations Secretary-General Ban Ki-moon (11/23/11) has aptly noted: "Climate change... could well trigger large-scale migration... These and other implications for peace and security have implications for the United Nations itself."

analytical studies in the climate change literature that look at individually-optimal migration decisions (Hoel and Shapiro 2003, Haavio 2005, Eppink and Withagen 2009, Marchiori et al. 2012), and even fewer analyze the decisions in a dynamic framework (Marchiori and Schumacher 2011).

The first analytical results in this literature have clearly shown that the feedback dynamics between migration and climate change are anything but negligible.[2] However, while analytical approaches to climate-induced migration are still rare, the empirical evidence is mounting. Apart from the well-known historical facts that climatic changes have played a role in toppling empires such as the Roman (Brooke 2014), there is also increasing evidence that climate change plays a role in more recent migration decisions (Kelley et al. 2015). It is clear that these large streams of immigration need to be managed and their consequences and implications require a thorough assessment. While these empirical studies show that climate-induced migration is already happening and likely to become an increasingly important phenomenon over the course of the next decades, it is also clear that not all regions are well-prepared for massive immigration and consequently conflicts are likely to arise (Stern 2013, Withagen 2014). While there is mounting evidence on the relationship between climate-induced migration and conflicts (Swain 1996, Raleigh and Urdal 2007, Reuveny 2007, Reuveny 2008, Salehyan 2008b, Hsiang et al. 2011, Maystadt and Ecker 2014), we are unaware of analytical approaches that jointly investigate the role of conflict in optimal mitigation and immigration decisions.

Hence, in this paper we review the recent literature and forward five simple theses on how conflicts, climate change and migration interact. Based upon this we then develop a theoretical framework that allows us to study these interactions more deeply. The framework we propose to investigate the links between conflict and optimal mitigation and migration policy is thus that a receiving region chooses the number of immigrants,[3] it wants from a pool of potential migrants

---

[2] "Permanent migration seems to occur because of irreversible or long-lasting problems like desertification or continuous environmental degradation that removes the subsistence possibility of people, or simply because people expect further extreme events in the future and try to avoid these" (Marchiori and Schumacher 2011).

[3] When it comes to international migration, the biggest barrier of international migration is the immigration policy in the receiving country. Thus, while there are models that have analyzed optimal migration decisions in a multi-country framework (Harris and Todaro 1970, Galor 1986) we believe that a single-region model, where migration decisions are endogenous but modeled in a black box, is sufficient to answer the questions we raise since immigration and mitigation policies tend to be undertaken unilaterally. Research on optimal immigration policies has focused on different aspects such as the impact on the labor market (Bencivenga and Smith 1997, Borjas 2003), the skill difference between natives and immigrants (Marchiori et al. 2014), pension systems (Razin

that is endogenously determined by the extent of climate change. Accepting these migrants allows increases in local production, but, as argued above, gives rise to internal conflicts. In addition, those potential migrants that are forced to move due to climate change but that are not allowed to immigrate may induce significant external conflict. Motivated by our five theses we assume that there is a probability of a conflict that is endogenous to the amount of potential migrants not admitted into the receiving country. We then allow a policy maker, in conjunction with his/her optimal mitigation policy, to dynamically choose the optimal number of immigrants. With this we want to understand the way a policy maker may wish to trade-off immigration and climate policies.

Our results suggest that immigration policy cannot any longer be separately studied from climate policy and that it is particularly the role of conflicts that drive optimal policy. In particular, if external conflict is judged to be the only important conflict then the North should take in all potential migrants without undertaking any mitigation policy. If a policy maker only perceives internal conflict as being important, then again no mitigation policy is necessary and the North would take in the GDP maximizing level of immigrants. Policy making becomes more complicated if there is reason to be believe that both conflicts co-exist. In this case multiple steady states exist and they are all subject to an active mitigation policy. More specifically, depending on parameters, either a corner steady state without immigration but with larger mitigation will be optimal, or an (high) interior steady state with a larger number of immigrants but less mitigation. Furthermore, we find the possibility of Skiba points, signaling that optimal policy depends on initial conditions, too. Thus, for levels of pollution at the Skiba point the policy maker can choose to cope with climate change-induced migration and related conflicts by placing more emphasis on mitigation and neglecting immigration, or by accepting migrants but neglecting mitigation. Hence, we would argue that additional criteria such as humanitarian or ethical ones, may need to supplement the purely economic trade-offs.

During transition we examine the substitutability and complementarity between the mitigation and immigration policy. If the high interior steady state is optimal, then we find that mitigation and immigration are complements on the transition path. If the corner steady state

---

and Sadka 1999), human capital formation (Vidal 1998), or the impact on income (Beine et al. 2001) and the distribution of wealth (Berry and Soligo 1969, Benhabib 1996), but to our knowledge immigration policy and conflict has not been investigated in relation to climate change and in dynamic frameworks that take feedbacks into account.

is optimal then for high levels of pollution both policies are initially substitutes but become complements closer to the steady state.

The article is structured as follows. In section 2 we discuss the links between climate change, migration and conflict. In section 3 we introduce the model. In section 4 we present the basic economic trade-offs related to the mitigation and immigration policy. Then we discuss the significant yet decisively different roles of the external and internal conflicts. We then turn to the analysis of the optimal solution. Section 5 concludes with further lessons and future research perspectives.

2 The links between climate change, migration and conflict

In this section we discuss some of the current knowledge on climate change, migration and conflict. This will not be an exhaustive reading of the literature, but it will provide a general perspective on what we know. We forward several theses[4] about the way these three topics interrelate, and present them in decreasing order based upon their empirical consensus. In the next section we then use the theses to motivate our modeling choices. We would also note that in this article conflict should be understood in a rather broad sense. The reader may simply understand this to be a monetary cost, or indeed a violent conflict.

Thesis 1 *Climate change triggers human migration.*

There is a general agreement about this in the literature across all disciplines. Climate change has been identified as a significant push factor and is expected to induce larger-scale migration in the future. In terms of numbers, however, estimates vary widely and depend on the climate change scenarios as well as nations' mitigation and adaptation strategies. As examples, during the past decades several million inhabitants from Bangladesh migrated to India for environmental reasons (Homer-Dixon 1991, Swain 1996), while roughly 2.5 million people migrated across the US due to the Great Dust Bowl in the 1930s (Worster 1982, Rosenzweig and Hillel 1993). It is now known that droughts in Burkina Faso and Sudan displaced around 1 million people in

---

[4] We shall not spend space on forwarding a thesis about the empirical consensus of economic activity as a driver of climate change since we believe that most readers should be knowledgeable about this. If not, read Pachauri et al. (2014).

the period 1968–1973 alone (Afolayan and Adelekan 1999, Hugo 1996), and more examples are found in Altan et al. (2006), Ezra (2001), Morris et al. (2002), Black et al. (2011), Mulligan et al. (2014), or Reuveny (2007). Recent empirical evidence suggests that climate change had at least an impact on the mass migration from Syria to Europe (Kelley et al. 2015, Hsiang and Burke 2014). Also, Feng et al. (2010) show that a 10% reduction in crop yields in Mexico leads to an additional 2% of Mexicans migrating to the US. Given the expected increases in climate change, predictions for climate-induced migration range from a few to several hundred million people in 2050 (Marchiori and Schumacher 2011, Gemenne 2011, Oppenheimer 2013).

There are some who argue that climate change may not increase migration (Field et al. 2014). Despite a somewhat conservative positioning of Field et al. (2014) there is ample empirical evidence coming from both microeconometric and macroeconomic studies that climatic changes has driven and will drive migration decisions across the world (Marchiori et al. 2015). Also, we more closely align ourselves with the forced migration literature, meaning that economic arguments are not necessarily underlying the migration choice, but that often migration may not be a choice but instead a necessity. This would, for example, be the case of desertification or sea level rise. Overall, sea level rise and desertification are expected to be the main push factors (Field et al. 2014). For sea level rise, estimates range from 72 million people (0.5 meter rise) to 187 million (2 meter rise) displaced people. For sub-Saharan Africa alone, higher predicted temperatures, and thus droughts and desertification, are expected to lead to an annual displacement of 12 million people by the end of this century (Marchiori et al. 2012).

While again there are some who believe that governments may heavily invest in protection measures (Hallegatte et al. 2011) and thereby significantly reduce migration needs, we would argue that it is not entirely clear or even unlikely that this is going to happen. After all, most of the people heavily affected by sea level rise or desertification are living in poor developing countries that often lack the institutional developments or finances which tend to be a prerequisite for taking protective actions. Furthermore, while most migration tends to be within national borders, WBGU (2009) suggest that "[t]ransboundary environmental migration will mainly take the form of south-south migration, but Europe and North America must also expect substantially increased migratory pressure from regions most at risk from climate change."[5]

Thesis 2 *Climate change promotes conflicts.*

---

[5] This is also confirmed in empirical studies, among others in Marchiori et al. (2012) and Feng et al. (2010).

When it comes to whether or not climate change promotes conflicts then there is increasing evidence supporting the thesis,[6] with some conflicting views[7] nevertheless. Hsiang et al. (2013) estimate, based on a meta-study, that for regions with strong expected climate change the frequency of inter-group conflicts may increase by up to 56%. In another study, Hsiang et al. (2011) find that El Nino may have been a major contribution to 21% of the 234 civil conflicts since 1950. Burke et al. (2009) estimate that climate change will increase armed conflicts in sub-Saharan Africa by 54% towards 2030. Similar results for the case of droughts are found in Couttenier and Soubeyran (2014). Though these results are not uncontested, see e.g. Gleditsch (1998) and Buhaug et al. (2014), it is generally accepted that climate change is, or can be, an additional factor that leads to conflicts. While it is certainly not the only factor, and definitely has not proven to be a sufficient factor, it is well-documented that environmental change induces, among others, social changes (Diamond 2005), undermines security and reinforces or even induces conflicts (Barnett and Adger 2007). Further support (see also Zhang et al. (2011)) for the relationship between climatic conditions and conflict come from Zhang et al. (2007), who study the period 1400-1900 and show that long-term fluctuations of war frequency and population changes followed the cycles of temperature change. In addition, von Uexkull (2014), studying sub-Saharan Africa for the period 1989-2008, emphasizes that droughts lead to a higher risk of civil conflict. For the case of India, Wischnath and Buhaug (2014) find that harvest loss leads to a higher probability of violence, and subsequently argue that climate change is likely to aggravate this relationship. In addition, studying North and South Sudan for the period 1997 and 2009, Maystadt et al. (2015) highlight that temperature anomalies increase the risk of future conflicts by around 27%. In the words of the German Advisory Council on Global Change (WBGU 2009), without adequate policy "... climate change will draw ever-deeper lines of division and conflict in international relations, triggering numerous conflicts between and within countries over the distribution of resources, especially water and land, over the management of migration, or over compensation payments between the countries mainly responsible for climate change and those countries most affected by its destructive effects."

In a good overview of the recent literature on climate change and conflicts, Salehyan (2014)

---

[6] The article by Jones (2011) contains a map of roughly 70 conflicts that occurred between 1980-2005 and that have been attributed to environmental factors, with water and land/soil being the predominant cause.

[7] There are, for example, studies suggesting that for some time periods and regions no impact from climate is found, e.g. O'Loughlin et al. (2012) or Ciccone (2011).

suggests that currently “the discussion is no longer about whether or not the climate influences conflict, but about when and how it does so.” It is here where we believe that we can provide some additional insights as to when a conflict may occur. However, we shall only focus on the link via migration and neglect the other potential array of arguments.

Thesis 3 *Climate change promotes conflicts through increased migration.*

In fact, there is evidence that already historically local environmental changes have led to large-scale migration that then induced conflicts. It is, for example, believed that droughts in Asia led to significant migration and consequently invasions by the Visigoths and Turks that helped topple the Roman Empire (Brooke 2014). Similarly, Yancheva et al. (2007) postulate that droughts led to migrations that contributed to the declines of the Chinese Tang dynasty and the Mayas in Central America. WBGU (2009) find that a large number of conflicts have been caused by environmental scarcities. And, going back even further in time, Büntgen et al. (2011) find that climate variability in the period 250 - 600 AD may have contributed to the Migration Period and the fall of the western Roman Empire. Out of the 38 cases of environmental migration identified by Reuveny (2007), 19 of these cases also see conflict in receiving regions. Reuveny (2007) specifically concludes by saying that “[e]nvironmental migration crosses international borders at times, and plays a role in conflict. Environmental migration does not always lead to conflict, but when it does, the conflict intensity can be very high, including interstate and intrastate wars.” Similarly, WBGU (2009) concludes that “[e]xperience has shown that migration can greatly increase the likelihood of conflict in transit and target regions.”

In order to provide a bit more structure on conflicts we shall now distinguish between two types of conflicts, namely internal and external conflict. When we refer to internal conflict we mean conflict that is due to immigration, thus we refer to costs of immigration. Instead, when we talk about external conflict we understand this as conflict that is caused by all those that potentially want to immigrate but are obstructed from doing so.

Thesis 4 *Immigration leads to internal conflicts.*

Immigration tends to have both benefits and costs for host countries, and this depends strongly on the type of immigration. Most studies have focused on immigration that occurs gradually and for economic reasons. In this respect, Borjas (1995) has argued that natives tend to benefit from immigration but that these benefits may be rather small. Kerr and Kerr (2011) survey the recent literature and find evidence that immigration leads to either very small or potentially negative work or wage displacement effects on natives. Public finances, however, do not tend to be negatively affected, but also only marginally positively. Thus, whereas it is clear that immigrants will add to overall GDP simply due to their additional labor (Aiyar et al. 2016), inhowfar additional benefits or costs occur is not entirely clear.[8]

Conflicts, however, tend to arise for larger levels of immigration because of internal social tensions that come directly from the difficult interaction between locals and the new foreign entrants (due to language barriers, cultural differences, downward pressure on wages, sharing of limited resources, etc. see e.g. Homer-Dixon (1991) and Withagen (2014)). In addition, one may expect increases in the crime rates or social unrest if the migrants are unable to directly contribute to the economy.[9] While empirical evidence for that is somewhat weak, a policy maker may nevertheless feel that this is a potential threat and thus introduce this cost when determining the immigration policy.[10]

However, it is clear that whenever immigrants start to compete for local resources with the inhabitants, then this is certainly breeding grounds for conflict (Hsiang et al. 2013). While we fully agree with Ostrom (1990) that good institutions may mediate conflict risk, it is also clear that at some point physical and financial constraints prevent countries (take Luxembourg as an extreme example) from taking on more immigrants, or that even good institutions cannot overcome the conflict between the natives and the immigrants. A thriving literature that has investigated this is the 'Sons of the Soil' literature and it has been reviewed in Côté and Mitchell

---

[8] With respect to the Syrian immigration, estimates suggest that, for Germany alone, annual costs of the refugees are expected to be around 10 billion euros (RWI 2015).

[9] For example, Angrist and Kugler (2003) show that immigrants to the European Union tend to have higher unemployment rates than locals, while Borjas (1995) argues that these differences tend to persist.... Borjas (1999) also shows that immigrants tend to choose their host country, among others, according to the welfare benefits.

[10] There is some evidence that the subjective assessment points strongly in this direction. For example, Mayda (2006) notes that "[b]oth security worries and cultural and national-identity issues are key non-economic factors affecting immigration opinions. Security concerns are related to the perception that immigrants are more likely than natives to be involved in criminal activity... Cultural and national-identity issues are related to the intrinsic side effect of immigration: the meeting, which often becomes a clash, of people of different ethnic origins and cultures."

(2015). One of the main contributions in this literature is Fearon and Laitin (2011) which concludes that around 1/3 of all ethnic civil wars since 1945 were between natives and immigrants.

In addition to this immigration for mostly economic reasons, the evidence cited above suggests that climate change leads to migration that is more forced than freely chosen, especially in the case of desertification or sea level rise. In this respect, Bhavnani and Lacina (2015) have found evidence for a statistically significant effect from climatic changes on interstate migration and subsequently conflict in India between 1982 and 2000. With a slightly more general focus, Salehyan and Gleditsch (2006) study the period 1951-2001 and find that international refugees increase the probability of conflict in the host country. Homer-Dixon (1994) has a number of case studies where he identifies environmental reasons as drivers for migration and subsequently conflict.

Thesis 5 *Constraining immigration leads to external conflicts.*

While the immigrants in the receiving country may give rise to some kind of an internal conflict, a potentially larger conflict may arise from those that want to immigrate but are not allowed. This not only significantly increases the conflict potential in the source countries (Hsiang et al. 2013), but it is now also getting more widely accepted that these conflicts may be taken to the recipient countries (Hsiang and Burke 2014, Homer-Dixon 1991). This thesis is a logical extension of the previous theses. In particular, we suggest the following channel at work. Assume there are people that want to migrate to their preferred region of choice, which we simply call the North, and to be more specific and link with our subsequent study (though this argument works for any push/pull factor) assume that climate change is the driver. If the North constrains the migrants from moving to their preferred location of choice, then they will end up in a less-preferred location. This location may be less-preferred simply because economic opportunities are worse or because social differences are larger. Consequently, given our literature synthesis above, this is likely to increase the risk of conflicts outside of the North. It is, furthermore, clear that the more the North constrains immigration the more likely will this external conflict occur.

This external conflict can then impact the North in various ways. For example, these conflicts can destabilize regions and lead to economic losses to the North (Murdoch and Sandler 2002) from reduced export demand, or it can require costly military interventions by the North to re-stabilize the region. Similarly, external conflicts are breeding grounds for terrorism that may take the war to the North itself (Backer et al. 2016), and thus constraining immigration may import conflicts (Salehyan 2008a). For example, Salehyan (2008a) notes that "[t]he Israeli invasion of Lebanon in 1982 and the Rwandan invasion of Zaire in 1996 were largely motivated by the desire to clear refugee camps that harbored militant factions." All these interventions are costly and one would expect the probability of having to intervene to be an increasing function of the number of potential immigrants not admitted.

Having reviewed these five theses regarding the link between climate change, migration, and conflict, the next Section sets out the model that will serve as a vehicle to the analysis.

3 A model of climate-induced migration and conflicts

In this article we focus on the optimal, unilateral decisions of the North.[11] The simple reason for focusing only on the North is that immigration policy tends to be undertaken unilaterally by the host countries, and, in light of the recent refugees crisis in Europe, it is clear that it is important to understand the determinants of immigration policy in the North. Furthermore, we focus on the North simply because most carbon emissions have historically arisen there, and also in terms of climate mitigation policy we expect the North to play the major role.

As we want to investigate the role of conflict for optimal climate and immigration policy in an analytically tractable framework, we will need to restrict the model by focusing on what we view as the most crucial aspects. As suggested above, we use an infinitely-lived, representative agent model, where a policy maker chooses the optimal mitigation and immigration policy. The policy maker is interested in total national income, where immigrants add to production while more production leads to further emissions which increases climate change. The stronger the impact of climate change on the poor, affected South, the more people want to migrate into the safer, wealthier North. The reason why a policy maker from the North may wish to obstruct immigration is because immigrants may give rise to an internal conflict. The reason for which a policy maker may wish to increase immigration is because this reduces the gap between potential immigrants and those migrants that are accepted into the country, and thus this reduces the likelihood of an external conflict. This is the basic model. We now go into more details on the

---

[11] There are of course many other approaches one can take, such as South-South migration or strategic interaction between the North and the South.

precise assumptions that we consider.

Production

Our assumption is that production, $G(I(t))$, in the North is the main driver of climate change. We abstract from population growth[12] in the North and assume that the total number of immigrants $I(t)$ into the North adds to total production, albeit with decreasing returns.

Assumption 1 *Total production in the North is a function of immigration* $I(t) > 0$ *and given by* $G(I(t))$, *with* $G(0) > 0$, $G'(I) > 0$, $G'(0) \in (0, \infty)$, *and* $G''(I) < 0$.

Thus, we take it that GDP in the North is at a steady state and can only be further increased by immigration. This functional form obviously comprises more detailed ones where we could distinguish the skills of the local population $\bar{L}$ (constant) with that of the immigrants $I(t)$ by assuming that the locals have a skill premium which could materialize e.g. in the form $G(\bar{L}+\alpha I(t))$ with $\alpha \in (0, 1)$, or that there are complementarities between locals and immigrants, $G(\bar{L}, I)$ with $G_{\bar{L}I} > 0$. The reduced form above comprises all these possibilities and, furthermore, that there may be another factor of production, like capital, which we assume to be constant in this basic model.[13]

Climate change

In line with empirical evidence, production in the North then is assumed to be the main source of climate change (Pachauri et al. 2014), and carbon emissions come as a fixed proportion $q_1 > 0$ of production. Thus, by accepting more immigrants the North also knows that this will induce further carbon emissions and consequently leads to an increased climate change.

In order to combat climate change, we assume that the North can invest in costly mitigation efforts, $A(t) > 0$. In order to not constrain ourselves to a particular technology we assume that

---

[12] While one could, of course, consider also the impact of population growth in the North, we would argue that this would only affect the results quantitatively. Also, realistically speaking, the population growth rate in the rich North is so low (roughly 0.5% on average in 2015) that we can easily abstract from this factor.

[13] According to our steady state perspective, the technology is actually given by $G(\bar{K}, \bar{L}, I)$, where both the capital stock and the size of the native population are taken constant. So, we abstract from the dynamics of capital and population.

the North has a whole array of technologies at its disposal, from simple abatement technologies that reduce emissions to carbon-capture and storage facilities that take carbon out of the atmosphere. For lack of better empirically-founded functional forms we assume that the mitigation technology is linear and simply attach a productivity parameter $q_2 > 0$ that measures how effective mitigation actions are in reducing carbon. However, in line with empirical evidence we take it that stronger mitigation efforts become more costly, with the mitigation cost being $c(A)$, with $c(A)$, $c'(A) > 0$ for all $A > 0$, $c(0) = c'(0) = 0$, and $c'' > 0$. Furthermore, carbon in the atmosphere is subject to natural decay due to natural forces like photosynthesis or ocean dynamics, and this natural decay comes at rate $\delta > 0$. As a result, we approximate the carbon cycle by

$$\dot{P}(t) = q_1 G(I(t)) - q_2 A(t) - \delta P(t), \tag{1}$$

with $P_0 \geq 0$ given, the level of carbon in the atmosphere when the North is at its initial condition.

In order for us to be able to clearly focus on the role of conflict for optimal mitigation and immigration policy we shall assume that the North is itself not directly affected by climate change. This assumption, by and large, is not far off from the results presented in various studies on regional impacts of climate change. We believe this to be a sufficiently realistic assumption for pollution levels that are not too extreme and outside of considerations for thresholds that lead to severe shifts in the earth's climate.[14] Nevertheless, its productive activities impose a negative externality on a block of countries, the South, that faces potentially severe environmental damages (extreme climate events, rise in sea levels etc.), which then trigger potential international migration.[15] Thus, we assume that the number of potential migrants increases with climate change. In particular, we assume that it increases linearly with the stock of carbon at rate

---

[14] We acknowledge that the assumption of the North being unaffected by climate change, especially if this climate change is very large, is a bit strong. However, in our model we follow the results from the IPCC and various integrated assessment models which show that, for smaller increases in temperature, the direct costs of climate change to the North are small. If one were to allow for significant impacts of climate change on the North then the North would obviously have incentives to curb climate change via mitigation.

[15] The expected number of climate migrants is somewhere around 150-200 million by 2050 (Stern 2007) and this number may significantly increase without adequate climate policy (Parry 2007). The stronger the climatic changes, the more severe will be the strain on the poorer populations and subsequently the larger will be number of potential migrants (Marchiori and Schumacher 2011). Based on back-of-the-envelope calculations, Marchiori and Schumacher (2011) have shown that it is not unreasonable to expect that the number of migrants may reach 35% of the population in the North by 2050. Assuming that these immigrants add to carbon emissions in a similar way as the local population would result in significant additional emissions.

$h > 0$, such that the number of potential migrants is given by $hP(t)$.[16]

In terms of choices for the North, we now know that it can choose the number of immigrants, denoted by $I(t)$, from the pool of potential migrations, such that $I(t) \in [0, hP(t)]$. Given this constraint, we can also define the maximum potential level of pollution, $\bar{P}$, which is the level of pollution that solves $q_1 G(h\bar{P}) = \delta \bar{P}$. This is the level of pollution at which all potential immigrants are allowed into the host country and in which no abatement is undertaken.

Internal conflict

History has shown us that countries tend to be, for a variety of reasons, unwilling to accept all the potential migrants.[17] As we have argued in Thesis 4, immigration may be costly for the locals in terms of labor market displacement effects, it may import terrorism, and it can lead to an internal conflict between immigrants and locals when strains are placed on limited resources.

We shall simplify and, without important losses to generality, assume that these internal conflicts are measurable in monetary terms by function $d(I)$, where $d(I), d'(I) > 0$ for all $I > 0$, $d(0) = d'(0) = 0$, and $d'' > 0$. Additionally, if one does not want to go down the road assuming that immigration leads to internal conflicts, then the cost $d(I)$ can also be interpreted as the costs of educational programs or constructing housing, both of which certainly do not come for free.

External conflict

Since our focus is on the optimal policy from the Northern perspective, we shall not model the conflicts arising in the South itself, but only concern ourselves with the likely conflict that the potential migrants that are not allowed to immigrate may take to the North. In other words, we assume that those migrants that are not accepted into the Northern territory may be the cause of an external conflict. While we have sufficient information on potential internal costs of immigration due to the world's larger experience with this, we have very little knowledge about the probability and depth of the external conflict that may arise due to climate change, as we

---

[16] We also investigated a more general functional form, given by $H(P)$, with $H(0) = 0$, $H' > 0$ and $H'' > 0$. The implications are sufficiently similar.

[17] For example, the US 'Secure Fence Act' of 2006 led to the construction of a 1,125 km long wall to deter Mexican migrants from freely entering the USA.

simply do not have enough observations on this. Thus, our choice to handle the internal conflict as deterministic seems reasonable, while the limited observations on climate-induced external conflicts requires us to treat the arrival of such events stochastically. The next assumption summarizes the way we treat the external conflict.

Assumption 2 *Let τ be the random variable representing the date at which an external conflict occurs. This variable is described by a probability distribution function $F(t) = \Pr(\tau < t)$ defined over the support $\mathbb{R}_+$, with endogenous density $f(t)$ defined as follows:*

$$f(t) = \psi(hP(t) - I(t))(1 - F(t)), \tag{2}$$

where $F(0) = 0$ given and $\psi(hP - I)$ is the hazard rate, with $\psi(0) = \psi'(0) = 0$, $\psi, \psi' > 0$, for $I \in [0, hP)$, and $\psi'' > 0$.

Consequently, the bigger the gap between potential migrants and immigrants, the larger will be the probability of an external conflict. We assume that the North loses a fixed utility cost $\kappa > 0$ in case the conflict materializes.[18] We model this in such a way that, if the negative event occurs, then the fixed cost is incurred but economic activities continue afterwards nevertheless. In order to obtain reasonable results we impose the following additional assumptions.

Assumption 3 *We impose $G'(0) > \frac{\rho+\delta}{hq_1}$.*

As we shall see later, this assumption insures that, at an optimal solution, abatement can effectively reduce the social cost of pollution. This condition basically requires that the first migrant's marginal impact on production is high enough.

In the last assumption, we define the criterion used in order to evaluate the instantaneous welfare effects of immigration and mitigation decisions.

Assumption 4 *Felicity function $u(Y(t))$ is a function of net income $Y(t) \geq 0$ which is given by $Y(t) = G(I(t)) - d(I(t)) - c(A(t))$, with function $u(Y(t))$ given by $u(Y(t)) : \mathcal{R}_+ \to \mathcal{R}$, with $u' > 0$, $u'' \leq 0$.*

---

[18] Thus, we endogenize the probability of an external conflict here, not the extent. This we do in a subsequent extension.

We are now ready to pull the components of the model together. As suggested before, the objective is to maximize the expected present value of utility, taking into account the costs from an uncertain external conflict that arises through the gap between potential migrants and immigrants; the costs from certain internal conflicts that arise through the immigrants; the costs of mitigating carbon to reduce the number of potential migrants; and the benefit of immigration, which yields increased local production. We undertake this exercise in an infinite horizon, stochastic optimal control problem, as it is clear that the various feedbacks require a dynamic treatment. Assume that the first external conflict, if any, occurs at time τ, then the objective functional is given by the following integral defined in terms of expectations

$$\mathbb{E}_\tau \left\{ \int_0^\tau u(Y(t))e^{-\rho t}dt + e^{-\rho\tau}(V(P(\tau)) - \kappa) \right\}, \tag{3}$$

where $\rho > 0$ is the discount rate, $V(P)$ denotes the value function, which also corresponds to the continuation payoff, and $\mathbb{E}_\tau$ is the expectation operator for the random variable. Let us define the survival probability, $X(t)$ as $X(t) = 1 - F(t)$. While the basic setup of the model is very much in line with the optimal control theory with an endogenous hazard (see especially Tsur and Zemel 2008, Tsur and Zemel 2009, van der Ploeg 2014), our problem is more complicated as it has both a stock and a control variable as part of the endogenous hazard.

Nevertheless, we can rewrite the problem in order to obtain its deterministic counterpart by relying on the Poisson nature of the hazard rate, which yields the full control problem given by

$$\max_{\{A(t),I(t)\}} \int_0^\infty \Big(u(G(I(t)) - d(I(t)) - c(A(t))) + \psi(hP(t) - I(t))\big(V(P(t)) - \kappa\big) \Big) X(t)e^{-\rho t}dt$$

subject to

$$\begin{cases} \dot{X}(t) = -\psi(hP(t) - I(t))X(t), \\ \dot{P}(t) = q_1 G(I(t)) - q_2 A(t) - \delta P(t), \\ I(t) \in [0, hP(t)], A(t) \geq 0 \text{ and } P_0,\ X_0(=1) \text{ given,} \end{cases} \tag{4}$$

To quickly recap, the questions that we want to address with this framework are as follows. When would the North have an incentive to cut its carbon emissions given the threat of conflict? Under what circumstances would the North find it worthwhile to implement an active immigration policy? How would an immigration policy interact with a climate policy? Can we derive conditions under which these policies are substitutes or complements? What will be the impact of the optimal mitigation and immigration policies on the evolution of the climate system?

4 Active mitigation vs. immigration policy

In order to solve the model we resort to standard optimization theory (Zemel 2015). The constant-value Lagrangian is given by

$$\begin{aligned}\mathcal{L} = &\left[u\big(G(I) - c(A) - d(I)\big) + \psi\big(hP - I\big)\big(V(P) - \kappa\big)\right] X + \\ &\lambda\big(q_1 G(I) - q_2 A - \delta P\big) - \mu\psi\big(hP - I\big)X + \phi_1 I + \phi_2(hP - I) + \phi_3 A\end{aligned} \tag{5}$$

with λ, μ the co-state variables respectively associated with the stock of pollution and the survival probability, and ϕ_1, ϕ_2 and ϕ_3 the Lagrange multipliers corresponding to the constraints respectively on I and A. We delegate as many of the mathematical derivations as possible into the appendix and concentrate on the main results and intuitions.

As of now, let us focus on the optimality conditions associated with the abatement and immigration decisions. They can be written as:[19]

$$\Lambda = -\frac{c'u'}{q_2} + \frac{\phi_3}{q_2 X}, \tag{6}$$

$$0 = u'(G' - d') + \kappa\psi' + \Lambda q_1 G' + \frac{\phi_1 - \phi_2}{X}, \tag{7}$$

Our aim is first to discuss the basic economic trade-offs at the interior solution with both positive abatement and positive but limited immigration by setting $\phi_i = 0$, for $i = 1, 2, 3$. Equation (6) equalizes the marginal gain of abatement, $-q_2\Lambda$, to the marginal cost of such a decision, $c'u'$. Clearly, an interior solution in abatement requires a negative shadow value of pollution ($\Lambda < 0$) as the policy maker would only want to reduce pollution if he or she also views pollution as being a cost.[20] Equation (7) depicts the trade-off related to a change in the level of migrants. According to (7), the North equalizes the marginal benefit of varying immigration I with the marginal cost. The gain is a lower risk of conflict which would cost the economy κ in terms of utility. An additional unit of I both increases production and the internal cost of migration. These two opposite effects, given by the difference $G' - d'$, are evaluated at the marginal utility u'. Depending on the level of immigration, this difference may be positive or negative. Moreover, the increase in output is also accompanied by an increase in emissions, $q_1 G'(I)$, and thus future pollution. pollution is damaging in this regime and its value is given by

---

[19] The whole set of optimality conditions is presented in Appendix A.

[20] If we were to assume that the North would also be affected by climate change then this would make it more likely that Λ is negative. It would, however, also further blur the subsequent results and not add more to intuition.

the shadow price $\Lambda < 0$. This second term always adds to the cost of immigration. Using (6), the optimality condition (7) can be rewritten as

$$\kappa\psi'(hP - I) = -u'(G(I) - d(I) - c(A))(G'(I)(1 - \frac{q_1}{q_2}c'(A)) - d'(I)). \tag{8}$$

The RHS must be positive, which is equivalent to $G'(I)(1 - \frac{q_1}{q_2}c'(A)) - d'(I) < 0$, for an interior regime with $A > 0$ and $I \in (0, hP)$ to be possible. Otherwise, it would mean that it is always beneficial to accept one more migrant, which would give a corner regime with $I = hP$. Condition (8) is crucial for the analysis of the interior regime because it defines a relationship between pollution, abatement and immigration that must hold a any instant spent therein: $P = \Phi(A, I)$, with

$$\Phi(I, A) = \frac{1}{h}\left[I + (\psi')^{-1}\left(-\frac{u'(G(I) - c(A) - d(I))(G'(I)(1 - \frac{q_1}{q_2}c'(A)) - d'(I))}{\kappa}\right)\right]. \tag{9}$$

It is useful to understand how pollution P responds to changes in mitigation A and immigration I. Following an increase in A, the economy's trade-off is modified as follows. For a given level of I, this increase directly reduces the available income, which in turns translates into an increase in the marginal utility. At the same time and from (6), it also raises the (negative) social value of pollution. Put differently, an increase in A makes the cost of abating emissions – caused by production and immigration – costlier (from the convexity of c). These two effects push in the same direction and make the net marginal cost of immigration higher. Therefore, following an increase in A, I being given, the stock of pollution has to increase to restore the equality in (9). This explains why $\Phi_A(A, I) > 0$. Moreover, from a concavity argument, we should have, other things equal, $\Phi_I(A, I) > 0$.

4.1 The roles of internal versus external conflict

Above we already alluded to the fact that both the external and internal conflict play significantly different yet very clear roles, but that only their interaction makes things complicated. In order to show that, we alternatively switch on the channels through which the internal and external conflict affect the mitigation and immigration policies.[21]

---

[21] Technical details can be derived from the analysis of the general case and are available upon request.

4.1.1 External conflict only

We start by assuming that a policy maker does not expect an internal conflict to occur. This would be a reasonable assumptions if there are no cultural or educational differences between locals and immigrants or if there is enough space and work for all immigrants. In other words, we assume that immigrants cannot be significantly distinguished from locals and that there are no negative returns from adding to population. Mathematically, this would be equivalent to assuming that $d(I) = 0$, $\forall I$.

In this situation, the solution is intuitively simple. Firstly, there is no cost of internal migration but instead only a benefit to income. Secondly, it is possible to minimize the external conflict by allowing all potential migrants to come in. Thus, the North should reap all the benefits and incur no cost by choosing no mitigation ($A = 0$) but accept all potential migrations ($I = hP$). Along the corresponding development trajectory, pollution increases monotonically to reach the maximum level of pollution $\bar{P}$ while its (positive) shadow value decreases.

While at first instance it seems unreasonable to accept that pollution may have a positive shadow value, or, in other words, that climate change may be something beneficial,[22] let us remind ourselves where this comes from. The North can benefit from climate change since this higher pollution leads to more potential migrants which help the North to increase its production. Since the North has the possibility to accept all potential migrants, then this minimizes the external conflict and immigrants subsequently become a source of North's economic growth. The fact that immigrants are, and have always been, a source of economic expansion in the receiving country is generally well accepted. We here add the point that climate change is likely to increase the number of potential migrants that the North may want to take in, and, if this is done, then in turn this may increase pollution and induce more migration.

4.1.2 Internal conflict only

The external conflict plays a drastically, significantly different role. If there were no external conflict, then a policy maker would be free to constrain the inflow of migrants to only the level up to which society benefits the most from these migrants. The reason is that without the

---

[22] Let us note that this result should not be surprising as overall mankind, ever since the industrial revolution, has benefited immensely from the emission of carbon.

external conflict there is no cost from not allowing potential migrants to enter the country. As a result, we can show that the North's valuation of pollution again is non-negative, and thus optimal abatement should always be zero.

Hence the policy maker should simply set immigration at the level that maximizes income, i.e. where $G'(I) = d'(I)$, $\forall t$, if the maximum attainable level of pollution is sufficiently high (i.e. $hP \geq I$). However, if the initial level of pollution is low, then the policy maker cannot set the number of immigrants at this level that maximizes net income (as there are not enough potential migrants), and consequently chooses the highest possible level, which is the one where he allows all potential migrants to immigrate. Clearly, the policy maker will then follow this policy up to the point where the number of potential migrants exceeds the level of immigrants that maximizes income minus internal conflict. From this point onwards the policy maker will keep the level of immigration at the income maximizing level.

We, by no means, suggest that it is necessarily a realistic scenario. However, even if we consider that the migrant-receiving country is affected by climate change then this result may continue to hold, especially if the impact of climate change is sufficiently low or if the North could undertake adaptation measures. Still, what we argue is that the North, if it is not (fully) driven by ethical considerations, would face the trade-offs as discussed above. As our model shows, even if the North were not to take e.g. the feedback from immigration on pollution into account, the results would still fully hold. The North would still set immigration at the maximum potential level if the number of potential migrants is below the income maximizing one, and would hold it at the income maximizing level otherwise. This shows the problems with such a unilateral policy and also demonstrates that there may be significant welfare gains if climate change policy were to be undertaken at the global level.

4.2 Optimal policy under internal and external conflicts

Let us now turn to the analysis of the general case. If we allow for both internal and external conflicts, then our system gives rise to a multitude of potential solutions and transitions between regimes. Based on the combinations between corner and interior solutions we can identify six potential regimes, each being characterized by a particular combination of mitigation, A, and immigration, I. One of these regimes ($A = 0, I = 0$) can be neglected since it cannot satisfy the necessary conditions (see the Appendix B). The remaining five regimes can all be represented in the $\Lambda - P$ space. Indeed, it is possible to define three regime curves, $\Lambda = 0$, $\Lambda = F_1(P)$, and $\Lambda = F_2(P)$, that divide this space into five different regions (see the Appendix A). As depicted in Figure 1, the horizontal axis splits the plan into the region with positive abatement (strictly below the axis) and the one with zero abatement (above and including the axis). $F_1(P)$ separates the region with full immigration from the one with only partial immigration whereas the location with respect to $F_2(P)$ tells us whether the economy accepts migrants, or not.[23] This is enough to locate the different regimes in the $\Lambda - P$ plan. The analysis in the $\Lambda - P$ plan proves to be very useful when it comes to the complete description of the global dynamics. We now investigate each regime separately in order to identify the potential outcomes in the long run.

4.2.1 Possible outcomes in the long run

Before going any further, we need to introduce some notations. Assume that the economy accepts all of the migrants and does not undertake any abatement so that the system lies in the regime $A = 0$, $I = hP$. The income, $G(hP) - d(hP)$, is inverted U-shaped, reaching a maximum for $P = \tilde{P}$. This yields a level of migrants such that the internal marginal gain from immigration equalizes the internal marginal cost, $G'(h\tilde{P}) = d'(h\tilde{P})$. Income must be non-negative, which requires $P \leq \bar{\bar{P}}$. Moreover the evolution of pollution is driven by the difference between emissions and natural absorption $q_1 G(hP) - \delta P$. This function is also inverted U-shaped with a maximum reached at $P = \check{P}$, $hq_1 G'(h\check{P}) = \delta$; the highest level of pollution attainable being given by $\bar{P}$ such that $q_1 G(h\bar{P}) = \delta \bar{P}$. Because of physical and economic constraints, pollution is constrained above by the minimum of $\bar{P}$ and $\bar{\bar{P}}$. Hereafter we take $\bar{P} < \bar{\bar{P}}$. As it is well-known that the concentration of CO_2 in the atmosphere is quite persistent (δ is low), the emissions-output ratio should be low as well.[24] In addition, the internal conflict function should not be too convex, meaning that serious conflicts may only occur when the number of migrants becomes sizable. Accordingly, we will assume that $\check{P} < \tilde{P}$ and furthermore, $\tilde{P} < \bar{P}$.[25]

For the remainder of the analysis, we need to introduce two last notations: let $\hat{P}$ and $\breve{P}$ be

---

[23] The regime curves $F_i(P)$, $i = 1, 2$, both start at $\Lambda = -u'(G(0) - c((c')^{-1}(\frac{q_2}{q_1}))/q_1$ for $P = 0$ and satisfy $F_1'(P) > 0$ and $F_2'(P) < 0$.

[24] This sounds like an acceptable assumption if one recognizes that the North has already reached a sufficiently advanced technological level so that the pollution intensity of production is quite low.

[25] This ranking corresponds to the most interesting situation featuring the largest variety of outcomes. A summary of what's going on under the other possible rankings is postponed to a later discussion.

respectively defined by $\rho + \delta = hq_1 G'(h\hat{P})$ and $\rho + \delta = hq_1 d'(h\breve{P})$. By construction we have $\hat{P} < \tilde{P} < \breve{P}$. Let us finally note that to each critical level of pollution corresponds a critical level of immigration given by $I = P/h$.

In Proposition 1, we establish which regime may host a steady state and derive the existence conditions (see the Appendix B).

Proposition 1 *The economy can end up in either the corner regime, with $A > 0$ and $I = 0$, or in the interior regime, with $A > 0$ and $I \in (0, hP)$.*

i. The steady state of the corner regime $A > 0, I = 0$ is a saddle point uniquely defined by:

$$\frac{q_1 G(0) - q_2 A}{\delta} = \frac{1}{h}(\psi')^{-1}\left(\frac{(\rho+\delta)c'(A)u'(G(0) - c(A))}{hq_2\kappa}\right).$$

This steady state exists only if: $G(0) > \max\left\{c((c')^{-1}(\frac{q_2}{q_1})), \frac{q_2}{q_1}(c')^{-1}(\frac{q_2}{q_1})\right\}$. It necessarily satisfies $A > (c')^{-1}(\frac{q_2}{q_1})$.

ii. Suppose that $I \geq \tilde{I}$ and $A \leq (c')^{-1}(\frac{q_2}{q_1})$. A steady state of the interior regime $A > 0, I \in (0, hP)$ solves:

$$\begin{aligned}
&(\rho+\delta)c'(A) + hq_2\big(G'(I)(1 - \tfrac{q_1}{q_2}c'(A)) - d'(I)\big) = 0 \Leftrightarrow A = A_1(I)\\
&q_1 G(I) - q_2 A - \delta\Phi(I, A) = 0 \Leftrightarrow A = A_2(I),
\end{aligned}$$

with Φ, the relationship linking P to A and I, defined in equation (9). There exists a unique steady state, which is a saddle point, if and only if $A_2(I) < A_1(I)$ at $I = \min\left\{\breve{I}, \bar{I}\right\}$.

The necessary conditions for a corner steady state requires the output, absent any immigration, be high enough. This sounds like an acceptable feature of the North developed economy. We also observe a kind of dichotomy in the nature of the long run outcome mostly coming from the level of abatement and how it compares to the threshold level $(c')^{-1}(\frac{q_2}{q_1})$. Moreover, focusing on large enough immigration levels ($I \geq \tilde{I}$) is sufficient to ensure that the necessary optimality condition (8), for an interior I, holds and $\Phi(I, A)$ is well-defined.

So this proposition basically states that the economy has two opposite options in the long run. Either it can settle in a long-run regime characterized by a high level of abatement and no immigration at all. This means that in order to control the threat of external conflict and to avoid any type of internal conflict, the policy maker chooses to keep the pollution level very low at the expense of production. At the other end of the spectrum of the possible decisions, the economy can stabilize at the interior solution for a level of abatement lower than the corner one. In this situation, it accepts quite a lot of migrants, which allows for a high level of production. As a byproduct of this policy, the level of pollution is higher than at the corner regime, while the risk of external conflict can be higher or lower than at the corner solution.

Note that we cannot rule out the existence of multiple interior solutions. In fact there may exist interior steady states in the region with $I < \tilde{I}$ (actually much lower, see the Appendix B.3) and $A > (c')^{-1}(\frac{q_2}{q_1})$. So they basically have the opposite properties as the unique interior steady state identified in Proposition 1 and can ultimately be interpreted as limit cases of the corner steady states with $A > 0$ and $I = 0$. As they do not bring much to the discussion, we do not elaborate more on this for now.

This simple steady state analysis emphasizes a substitutability between the two policy instruments, mitigation and immigration. In the next section, we go one step further by examining the global dynamics. The aim is to address a series of questions: what are the development paths that may bring the economy to the possible steady states? Are mitigation and immigration policies substitute or complement along these paths? What is the optimal policy? To answer these questions, we have to take a look at the dynamical system in each particular regime and investigate the possible combinations of these regimes.

4.2.2 Dynamic behavior and optimality

For the sake of simplicity, we impose two restrictions henceforth: we assume that the utility function u is linear (so we work directly with income as the objective function) and that the costs of mitigation, $c(A)$, are quadratic. As mentioned just above, there may also exist low interior steady states featuring $I < \tilde{I}$. If it is quite easy to give a sufficient existence condition for this type of interior steady state, it proves more difficult to assess their number and stability properties. In the following discussion we will consider a situation similar to the one depicted in Figure 1, in which there is another interior steady state, whose location is close to the F_2 frontier, featuring low immigration and high abatement. This indeed leads to the most familiar configuration with three steady states, of which the intermediate one is a source.[26]

It is clearly visible that the economy may exhibit a wide range of more or less complex dynamic behaviors (including several transitions between regimes). But, given Proposition 1, we know that the optimal path will end up in the steady state of either the corner regime with no immigration (bottom, left), or the interior regime (middle, right). Which steady state then turns out to be the optimal one depends on the parameters of the model. In particular, we find that (albeit numerically only) for some parameter combinations the high interior steady state turns out to be optimal, for some the corner steady state, while for others there exists a Skiba point (Skiba 1978)[27] and which steady state is optimally approached asymptotically then depends on the initial condition of pollution.

Let us assume that the parameter conditions are such that the high interior steady state is optimal, as depicted in Figure 1. For illustration purposes we consider that initial pollution is low. In this case the policy maker finds it optimal to choose $\Lambda_0 \geq 0$ since low pollution means that both internal and external conflict is at a very low level. Hence the North will choose a development path (depicted by the red curve in the figure) where it first neglects investment in mitigation and accepts as many immigrants as possible for a while. This places the economy on a trajectory of increasing pollution and increasing number of immigrants. This (temporary) negligence of climate policy can have two reasons. Intuitively, it can be motivated by purely self-centered motives, whereby the North may decide to accept few migrants in order to prevent any (initial) risk of external conflict. This can be all the more optimal as in this region increasing P and I has an overall positive impact on the economy because initially the costs of internal and external conflict are very low.

After some point, however, the North finds that the increase in immigrants finally induces some non-negligible levels of internal conflict, which would imply that the benefits from increasing climate change shrink. If that is the case, the economy switches in the regime with $A > 0$ and $I = hP$, which means that the policy maker wishes to start mitigation efforts in order to reduce the number of climate refugees. The policy maker knows that as he/she increases the number of migrants, immigration leads to an internal conflict (the internal benefits from immigration gets

---

[26] This situation is indeed the only one that comes out in our numerical analysis once we impose $A_1(0) < A_2(0)$.

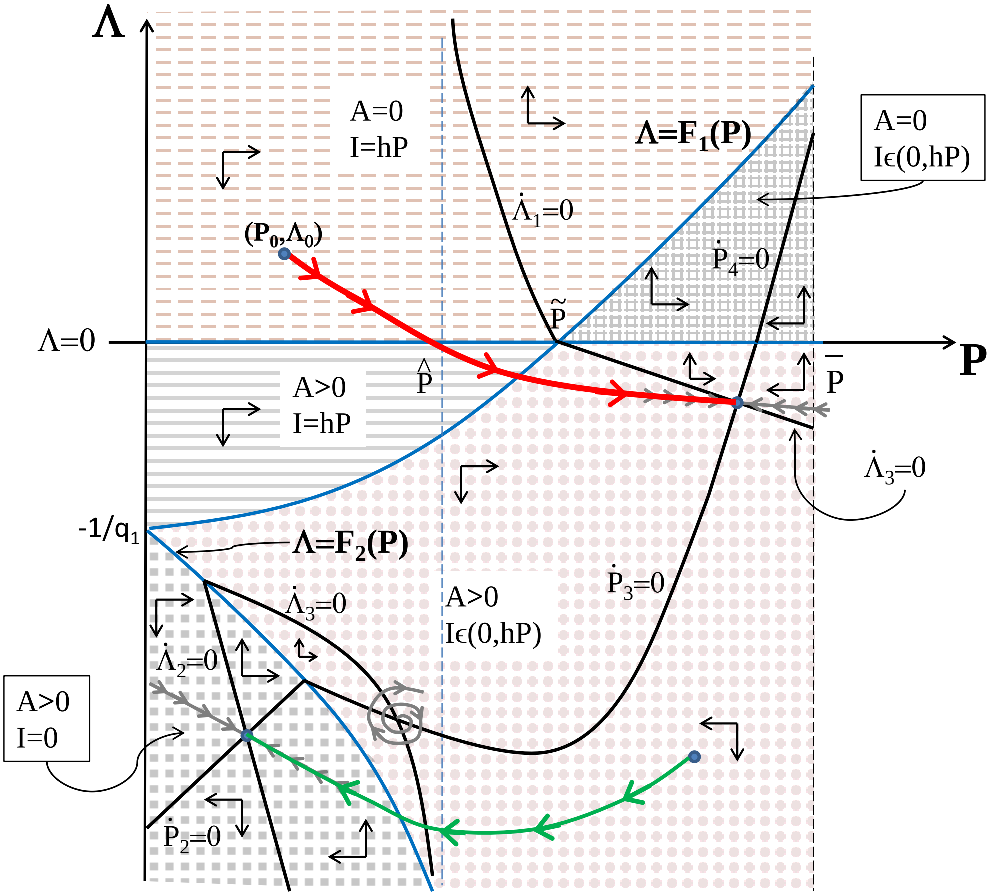
[27] We thank Florian Wagener for the suggestion to search for Skiba points and refer the reader to Wagener (2003) for a rigorous analysis of Skiba points and their link with the bifurcation theory.

exhausted) while at the same time it increases external conflict through the impact of production on climate change; and subsequently the number of potential migrants. Mitigation can help in this case to slow down the process, i.e., to compensate for the increased impact of production on climate change from immigration since some of the GDP that immigration produces can be used for mitigation. Finally, when the stock of pollution and the number of potential migrants become high enough, the North tightens its immigration policy (regime $A > 0$, $I < hP$) and accepts to bear the risk of external conflict in order to keep internal conflict under control. Last but not least, this discussion highlights that on the optimal way to the high interior steady state both mitigation are immigration are never substitutes but tend to be chosen as complements.

As a more policy-oriented conclusion and in the light of the Syrian refugee crisis, which some argue has partly been caused by climatic changes, we suggest that Europe is currently in regime $A > 0$, $I = hP$: some mitigation action is undertaken to reduce climate change, and a significant amount of immigration is accepted. The overall value of more climate change now starts to be perceived being negative since increases to climate change would drive more migrants into Europe. Hence the economy should switch in finite time to regime $A > 0$, $I \in (0, hP)$ where there is a (saddle path) stable equilibrium, implying that also in future there will be a large number of Syrian immigrants in Europe, while mitigation efforts are likely to increase in order to reduce total immigration. From the discussion of Section 4.1.1, we may argue that the trajectory should give the optimum for a sufficiently small enough internal conflict, a high risk of external conflict and expensive mitigation.

On the other hand, it is possible that the North is neither concerned much with a potential external conflict, nor does it feel that migrants add sufficiently to the region's income in order to find that immigration is worthwhile. This, for example, could be the case of the USA, a region that blocks immigration from Mexico for precisely those two reasons. However, let us furthermore assume that, despite the recent European experience, this rich region has sufficient foresight and is able to acknowledge that the current way of producing leads to emissions that would increase the number of potential immigrants. Not willing to accept the rise in the pool of potential migrants, the North decides to undertake substantial mitigation. This would place the system in regime $A > 0$, $I = 0$ where the North does not accept immigration, yet at the same time reduces climate change in order to lower the potential for external conflict. For this trajectory to be optimal, it must be that the mitigation option is actually cheap enough, or sufficiently efficient. If that is not the case, then the solution with positive mitigation but zero immigration is not the best choice and it becomes relatively cheaper to actually allow for some immigration.

Figure 1: Graphical representation of optimal solution



Let us precisely take the case where the internal conflict is of high significance while mitigation is sufficiently cheap such that the optimal solution ends up in the corner regime ($I = 0$, $A > 0$). In this situation, and for sufficiently high levels of pollution, the optimality candidate is similar to the green curve depicted in Figure 1. We find that the North always chooses an interior level of immigration first in order to reduce the importance of the external conflict. But at the same time it uses mitigation in order to bring pollution down again. Along the optimal path, the mitigation and immigration policy are then substitutes. They are substitutes insofar as the North invests significantly in mitigation in order to be able to reduce immigration. Once the North has managed to reduce pollution significantly it will start to slow down both mitigation and immigration and stop accepting migrants eventually. In this case, the North can afford to live with a certain relatively low risk of external conflict, yet benefiting from not having the more significant internal conflict.

We finally look at the case where the North recognizes the importance of both internal and external conflict and does not have a sufficiently cheap abatement option. In this case either of the two possible development trajectories, leading to the two different steady states, can be a candidate for optimality and the initial level of pollution determines which one should be optimally approached. Indeed for some parameter values, we find a Skiba point, defined as the critical initial level of pollution at which the North is indifferent between taking the path that leads to the corner steady state and following the trajectory that brings the economy to the high interior steady state.[28] It is also important to notice that in this situation, the policy maker never attaches a positive value to pollution. For any initial level of pollution, it is always better to either reduce pollution or slow down its growth.

5 Conclusion

In this article we investigated the links between conflict and optimal mitigation and immigration policy. We forwarded five theses that we base on a summary of the recent literature. These theses are that climate change triggers human migration, it promotes conflicts, and it more specifically promotes those conflicts through increased migration, and finally that immigration leads to internal conflicts while constraining immigration can aggravate external conflicts. Based upon these theses we developed a model where a receiving region chooses the number of immigrants it wants to accept from a pool of potential migrants that is endogenously determined by the extent of climate change. Accepting these migrants allows increases in local production, but, as argued above, gives rise to internal conflicts. In addition, those potential migrants that are forced to move due to climate change but that are not allowed to immigrate may induce significant external

---

[28] For any level of pollution below (above) the Skiba point, the economy will optimally end up in the corner (interior) regime.

conflict. We then allow a policy maker, in conjunction with his/her optimal mitigation policy, to dynamically choose the optimal number of immigrants in this framework. With this we want to understand the way a policy maker may wish to trade-off immigration and climate policies.

Our results suggest that immigration policy cannot any longer be separately studied from climate policy and that it is particularly the role of conflicts that drive optimal policy. In particular, if external conflict is judged to be the only important conflict then the North should take in all potential migrants without undertaking any mitigation policy. If a policy maker only perceives internal conflict as being important, then again no mitigation policy is necessary and the North would take in the GDP maximizing level of immigrants. Instead, policy making becomes more complicated if there is reason to be believe that both conflicts co-exist. In this case multiple steady states exist and they are all subject to an active mitigation policy. More specifically, depending on parameters, either a corner steady state without immigration but with larger mitigation will be optimal, or an (high) interior steady state with a larger number of immigrants but less mitigation. Furthermore, we find the possibility of Skiba points, signaling that optimal policy depends on initial conditions, too. Thus, for levels of pollution at the Skiba point the policy maker can choose to cope with climate change-induced migration and related conflicts by placing more emphasis on mitigation and neglecting immigration, or by accepting migrants but neglecting mitigation. Hence, we would argue that additional criteria such as humanitarian or ethical ones, may need to supplement the purely economic trade-offs. These results also blur the distinction between action and responsibility, for the increase in migrants induces further climate change. However, who then is responsible for this increase - the North who accepted the migrants or the South from where these additional migrants came? How should this affect damage attribution and inhowfar could the North then be held responsible for the losses in the South? Furthermore, it is difficult to distinguish between the North accepting more migrants for humanitarian reasons, or simply because they help further economic expansion. We cannot answer these questions within this framework and also do not view this as our task here, but our model here helps in pointing out that these questions deserve a closer analysis and, in the light of the model's results, may turn out to be more difficult to answer than one would expect.

In terms of future research we suggest to work on the following. Firstly, we desperately need more empirical evidence on the precise costs, probabilities and extends of national and international conflicts that are due to migration from climate change. While it seems even the IPCC dismisses the possibility of large-scale climate migration (though even within the report there are conflicting views), examples like the Syrian conflict show that even smaller climatic shocks may aid or even trigger destabilization in countries or regions that then induces significant migration waves and humanitarian crises. The situation becomes much more difficult to predict once we are in a high carbon emission scenario with significant global temperature increases. In terms of theoretical work, one may argue that the shape of the social welfare function matters a lot. Rather than considering a standard utility function defined on aggregate income, one may alternatively choose the average utilitarian criterion. One may want to add capital accumulation and demographic aspects, or one may want to investigate the impact of cost of border controls. Additionally, the literature suggests that institutions do play an important role for the probability of conflicts between migrants and natives, and thus the development of institutions may be another important focus of theoretical work.

References

Afolayan, AA and IO Adelekan, "The role of climatic variations on migration and human health in Africa," *Environmentalist*, 1999, *18* (4), 213–218.

Aiyar, Shekhar, Bergljot Barkbu, Nicoletta Batini, Helge Berger, Enrica Detragiache, Allan Dizioli, Christian Ebeke, Huidan Lin, Linda Kaltani, Sebastian Sosa, Antonio Spilimbergo, and Petia Topalova, "The Refugee Surge in Europe," 2016.

Altan, Orhan et al., "The Contribution of the Surveying Profession to Disaster Risk Management," *A publication of FIG Working Group*, 2006, *8.*

Angrist, Joshua D and Adriana D Kugler, "Protective or counter-productive? labour market institutions and the effect of immigration on eu natives," *The Economic Journal*, 2003, *113* (488), F302–F331.

Backer, David, Ravinder Bhavnani, and Paul Huth, *Peace and Conflict 2016*, Routledge, Center for International Development and Conflict Management, 2016.

Barnett, Jon and W Neil Adger, "Climate change, human security and violent conflict," *Political Geography*, 2007, *26* (6), 639–655.

Beine, Michel, Frédéric Docquier, and Hillel Rapoport, "Brain drain and economic growth: theory and evidence," *Journal of development economics*, 2001, *64* (1), 275–289.

Bencivenga, Valerie R and Bruce D Smith, "Unemployment, migration, and growth," *Journal of Political Economy*, 1997, *105* (3), 582–608.

Benhabib, Jess, "On the political economy of immigration," *European Economic Review*, 1996, *40* (9), 1737–1743.

Berry, R Albert and Ronald Soligo, "Some welfare aspects of international migration," *The Journal of Political Economy*, 1969, pp. 778–794.

Bhavnani, Rikhil R and Bethany Lacina, "The Effects of Weather-Induced Migration on Sons of the Soil Riots in India," *World Politics*, 2015, *67* (04), 760–794.

Black, Richard, Stephen RG Bennett, Sandy M Thomas, and John R Beddington, "Climate change: Migration as adaptation," *Nature*, 2011, *478* (7370), 447–449.

Borjas, George J, "The Economic Benefits from Immigration," *The Journal of Economic Perspectives*, 1995, *9* (2), 3–22.

Borjas, George J., "Immigration and Welfare Magnets," *Journal of Labor Economics*, 1999, *17* (4), 607–637.

Borjas, George J, "The Labor Demand Curve Is Downward Sloping: Reexamining the Impact of Immigration on the Labor Market," *The Quarterly Journal of Economics*, 2003, *118* (4), 1335–1374.

Bosetti, Valentina, Carlo Carraro, Marzio Galeotti, Emanuele Massetti, and Massimo Tavoni, "A world induced technical change hybrid model," *The Energy Journal*, 2006, *27*, 13–38.

Brooke, John L., *Climate change and the course of global history: a rough journey*, Cambridge University Press, 2014.

Buhaug, Halvard, J Nordkvelle, T Bernauer, T Böhmelt, M Brzoska, JW Busby, A Ciccone, Hanne Fjelde, E Gartzke, NP Gleditsch et al., "One effect to rule them all? A comment on climate and conflict," *Climatic Change*, 2014, *127* (3-4), 391–397.

Büntgen, Ulf, Willy Tegel, Kurt Nicolussi, Michael McCormick, David Frank, Valerie Trouet, Jed O Kaplan, Franz Herzig, Karl-Uwe Heussner, Heinz Wanner et al., "2500 years of European climate variability and human susceptibility," *Science*, 2011, *331* (6017), 578–582.

Burke, Marshall B, Edward Miguel, Shanker Satyanath, John A Dykema, and David B Lobell, "Warming increases the risk of civil war in Africa," *Proceedings of the National Academy of Sciences*, 2009, *106* (49), 20670–20674.

Ciccone, Antonio, "Economic Shocks and Civil Conflict: A Comment," *American Economic Journal: Applied Economics*, October 2011, *3* (4), 215–27.

Côté, Isabelle and Matthew I Mitchell, "Deciphering ‚ÄòSons of the Soil‚ÄôConflicts: A Critical Survey of the Literature," *Ethnopolitics*, 2015, pp. 1–19.

Couttenier, Mathieu and Raphael Soubeyran, "Drought and Civil War In Sub-Saharan Africa," *The Economic Journal*, 2014, *124* (575), 201–244.

Diamond, Jared, *Collapse: How societies choose to fail or succeed*, Penguin, 2005.

Eppink, Florian V and Cees A Withagen, "Spatial patterns of biodiversity conservation in a multiregional general equilibrium model," *Resource and energy economics*, 2009, *31* (2), 75–88.

Ezra, Markos, "Ecological degradation rural poverty and migration in Ethiopia: a contextual analysis.," 2001.

Fearon, James D and David D Laitin, "Sons of the soil, migrants, and civil war," *World Development*, 2011, *39* (2), 199–211.

Feng, Shuaizhang, Alan B Krueger, and Michael Oppenheimer, "Linkages among climate change, crop yields and Mexico–US cross-border migration," *Proceedings of the National Academy of Sciences*, 2010, *107* (32), 14257–14262.

Field, Christopher B, Vicente R Barros, K Mach, and M Mastrandrea, *Climate change 2014: impacts, adaptation, and vulnerability*, Vol. 1, Cambridge University Press Cambridge, New York, NY, 2014.

Galor, Oded, "Time preference and international labor migration," *Journal of Economic Theory*, 1986, *38* (1), 1–20.

Gemenne, François, "Climate-induced population displacements in a 4 C+ world," *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 2011, *369* (1934), 182–195.

Gleditsch, Nils Petter, "Armed conflict and the environment: A critique of the literature," *Journal of peace research*, 1998, *35* (3), 381–400.

Golosov, Mikhail, John Hassler, Per Krusell, and Aleh Tsyvinski, "Optimal taxes on fossil fuel in general equilibrium," *Econometrica*, 2014, *82* (1), 41–88.

Haavio, Markus, "Transboundary pollution and household mobility: Are they equivalent?," *Journal of Environmental Economics and Management*, 2005, *50* (2), 252–275.

Hallegatte, Stéphane, Fanny Henriet, and Jan Corfee-Morlot, "The economics of climate change impacts and policy benefits at city scale: a conceptual framework," *Climatic Change*, 2011, *104* (1), 51–87.

Harris, John R and Michael P Todaro, "Migration, unemployment and development: a two-sector analysis," *The American economic review*, 1970, pp. 126–142.

Hoel, Michael and Perry Shapiro, "Population mobility and transboundary environmental problems," *Journal of Public Economics*, 2003, *87* (5), 1013–1024.

Homer-Dixon, Thomas F, "On the threshold: environmental changes as causes of acute conflict," *International security*, 1991, pp. 76–116.

____ , "Environmental scarcities and violent conflict: evidence from cases," *International security*, 1994, *19* (1), 5–40.

Hsiang, Solomon M and Marshall Burke, "Climate, conflict, and social stability: what does the evidence say?," *Climatic Change*, 2014, *123* (1), 39–55.

___ , Kyle C Meng, and Mark A Cane, "Civil conflicts are associated with the global climate," *Nature*, 2011, *476* (7361), 438–441.

___ , Marshall Burke, and Edward Miguel, "Quantifying the influence of climate on human conflict," *Science*, 2013, *341* (6151), 1235367.

Hugo, Graeme, "Environmental concerns and international migration," *International migration review*, 1996, pp. 105–131.

Jones, Nicola, "Heating up tensions," *Nature Climate Change*, 2011, *1* (7), 327–329.

Kelley, Colin P, Shahrzad Mohtadi, Mark A Cane, Richard Seager, and Yochanan Kushnir, "Climate change in the Fertile Crescent and implications of the recent Syrian drought," *Proceedings of the National Academy of Sciences*, 2015, *112* (11), 3241–3246.

Kerr, Sari Pekkala and William R Kerr, "Economic impacts of immigration: A survey," Technical Report, National Bureau of Economic Research 2011.

Manne, Alan S and Richard G Richels, "MERGE: an integrated assessment model for global climate change," in "Energy and Environment," Springer, 2005, pp. 175–189.

Marchiori, Luca and Ingmar Schumacher, "When nature rebels: international migration, climate change, and inequality," *Journal of Population Economics*, 2011, *24* (2), 569–600.

___ , Jean-François Maystadt, and Ingmar Schumacher, "The impact of weather anomalies on migration in sub-Saharan Africa," *Journal of Environmental Economics and Management*, 2012, *63* (3), 355–374.

___ , ___ , and ___ , "Is environmentally induced income variability a driver of human migration?," *Migration and Development*, 2015, pp. 1–27.

___ , Patrice Pieretti, and Benteng Zou, "Immigration, occupational choice and public employment," *Institute of Mathematical Economics Working Paper*, 2014, (516).

Mayda, Anna Maria, "Who is against immigration? A cross-country investigation of individual attitudes toward immigrants," *The Review of Economics and Statistics*, 2006, *88* (3), 510–530.

Maystadt, Jean-François and Olivier Ecker, "Extreme Weather and Civil War: Does Drought Fuel Conflict in Somalia through Livestock Price Shocks?," *American Journal of Agricultural Economics*, 2014, *96* (4), 1157–1182.

____, Margherita Calderone, and Liangzhi You, "Local warming and violent conflict in North and South Sudan," *Journal of Economic Geography*, 2015, *15* (3), 649–671.

McLeman, Robert, "Developments in modelling of climate change-related migration," *Climatic Change*, 2013, *117* (3), 599–611.

Morris, Saul S, Oscar Neidecker-Gonzales, Calogero Carletto, Marcial Munguı?a, Juan Manuel Medina, and Quentin Wodon, "Hurricane Mitch and the livelihoods of the rural poor in Honduras," *World development*, 2002, *30* (1), 49–60.

Mulligan, Mark, Sophia Burke, and Caitlin Douglas, "Environmental Change and Migration Between Europe and Its Neighbours," in "People on the Move in a Changing Climate," Springer, 2014, pp. 49–79.

Murdoch, James C and Todd Sandler, "Economic growth, civil wars, and spatial spillovers," *Journal of conflict resolution*, 2002, *46* (1), 91–110.

Nordhaus, W. D. and Z. Yang, "A regional dynamic general-equilibrium model of alternative climate-change strategies," *The American Economic Review*, 1996, pp. 741–765.

Nordhaus, William, "Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches," *Journal of the Association of Environmental and Resource Economists*, 2014, *1* (1), 273–312.

Nordhaus, William D, *A question of balance: Weighing the options on global warming policies*, Yale University Press, 2014.

O'Loughlin, John, Frank DW Witmer, Andrew M Linke, Arlene Laing, Andrew Gettelman, and Jimy Dudhia, "Climate variability and conflict risk in East Africa, 1990–2009," *Proceedings of the National Academy of Sciences*, 2012, *109* (45), 18344–18349.

Oppenheimer, Michael, "Climate change impacts: accounting for the human response," *Climatic Change*, 2013, *117* (3), 439–449.

Ostrom, Elinor, *Governing the commons: The evolution of institutions for collective action*, Cambridge: Cambridge University Press, 1990.

Pachauri, Rajendra K, MR Allen, VR Barros, J Broome, W Cramer, R Christ, JA Church, L Clarke, Q Dahe, P Dasgupta et al., "Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," 2014.

Parry, Martin L, *Climate Change 2007: impacts, adaptation and vulnerability: contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change*, Vol. 4, Cambridge University Press, 2007.

Peck, SC and Teisberg TJ, "CO2 emissions control agreements: incentives for regional participation," *The Energy Journal*, 1999, *20*, 367ÔøΩ390.

Ploeg, Frederick and Cees Withagen, "Growth, renewables, and the optimal carbon tax," *International Economic Review*, 2014, *55* (1), 283–311.

Raleigh, Clionadh and Henrik Urdal, "Climate change, environmental degradation and armed conflict," *Political geography*, 2007, *26* (6), 674–694.

Razin, Assaf and Efraim Sadka, "Migration and pension with international capital mobility," *Journal of Public Economics*, 1999, *74* (1), 141–150.

Reuveny, Rafael, "Climate change-induced migration and violent conflict," *Political Geography*, 2007, *26* (6), 656–673.

____ , "Ecomigration and violent conflict: Case studies and public policy implications," *Human Ecology*, 2008, *36* (1), 1–13.

Risse, Mathias, "On the morality of immigration," *Ethics & International Affairs*, 2008, *22* (1), 25–33.

Rosenzweig, Cynthia and Daniel Hillel, "The dust bowl of the 1930s: Analog of greenhouse effect in the Great Plains?," *Journal of Environmental Quality*, 1993, *22* (1), 9–22.

RWI, "Die wirtschaftliche Entwicklung im Ausland und im Inland zur Jahresmitte 2015," Technical Report, Jahrgang 66 (2015) Heft 3 2015.

Salehyan, Idean, "The externalities of civil strife: Refugees as a source of international conflict," *American Journal of Political Science*, 2008, *52* (4), 787–801.

——, "From climate change to conflict? No consensus yet," *Journal of Peace Research*, 2008, *45* (3), 315–326.

——, "Climate change and conflict: making sense of disparate findings," *Political Geography*, 2014, *43*, 1–5.

—— **and Kristian Skrede Gleditsch**, "Refugees and the spread of civil war," *International Organization*, 2006, *60* (02), 335–366.

Skiba, A.K., "Optimal growth with a concave-convex production function," *Econometrica*, 1978, *46* (03), 527–539.

Stern, Nicholas, *The economics of climate change: the Stern review*, cambridge University Press, 2007.

——, "The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models," *Journal of Economic Literature*, 2013, *51* (3), 838–859.

Swain, Ashok, "Environmental migration and conflict dynamics: focus on developing regions," *Third World Quarterly*, 1996, *17* (5), 959–974.

Tol, Richard SJ, "On the optimal control of carbon dioxide emissions: an application of FUND," *Environmental Modeling & Assessment*, 1997, *2* (3), 151–163.

Tsur, Yacov and Amos Zemel, "Regulating environmental threats," *Environmental and Resource Economics*, 2008, *39* (3), 297–310.

—— **and** ——, "Endogenous discounting and climate policy," *Environmental and Resource Economics*, 2009, *44* (4), 507–520.

van der Ploeg, Frederick, "Abrupt positive feedback and the social cost of carbon," *European Economic Review*, 2014, *67*, 28–41.

Vidal, Jean-Pierre, "The effect of emigration on human capital formation," *Journal of Population Economics*, 1998, *11* (4), 589–600.

von Uexkull, Nina, "Sustained drought, vulnerability and civil conflict in Sub-Saharan Africa," *Political Geography*, 2014, *43*, 16–26.

Wagener, Florian OO, "Skiba points and heteroclinic bifurcations, with applications to the shallow lake system," *Journal of Economic Dynamics and Control*, 2003, *27* (9), 1533–1561.

WBGU, *Climate change as a security risk*, German Advisory Council on Global Change (WBGU), Earthscan, London and Sterling, VA, 2009.

Wischnath, Gerdis and Halvard Buhaug, "Rice or riots: On food production and conflict severity across India," *Political Geography*, 2014, *43*, 6–15.

Withagen, Cees, "The climate change, migration and conflict nexus," *Environment and Development Economics*, 2014, *19* (03), 324–327.

Worster, Donald, *Dust bowl: the southern plains in the 1930s*, Oxford University Press, 1982.

Yancheva, Gergana, Norbert R Nowaczyk, Jens Mingram, Peter Dulski, Georg Schettler, Jörg FW Negendank, Jiaqi Liu, Daniel M Sigman, Larry C Peterson, and Gerald H Haug, "Influence of the intertropical convergence zone on the East Asian monsoon," *Nature*, 2007, *445* (7123), 74–77.

Zemel, Amos, "Adaptation, mitigation and risk: an analytical approach," *Journal of Economic Dynamics and Control*, 2015, *51*, 133–147.

Zhang, David D, Harry F Lee, Cong Wang, Baosheng Li, Qing Pei, Jane Zhang, and Yulun An, "The causality analysis of climate change and large-scale human crisis," *Proceedings of the National Academy of Sciences*, 2011, *108* (42), 17296–17301.

____, Peter Brecke, Harry F Lee, Yuan-Qing He, and Jane Zhang, "Global climate change, war, and population decline in recent human history," *Proceedings of the National Academy of Sciences*, 2007, *104* (49), 19214–19219.

A Regime curves

Using standard techniques, the necessary optimality conditions (NOC) associated with problem (4) can be written as

$$\begin{aligned}
\Lambda &= -\frac{c'u'}{q_2} + \frac{\phi_3}{q_2 X}, && (10)\\
0 &= u'\big(G' - d'\big) + \kappa\psi' + q_1\Lambda G' + \frac{\phi_1 - \phi_2}{X}, && (11)\\
\dot{\Lambda} &= (\rho + \delta)\Lambda + \kappa h\psi' - \frac{h\phi_2}{X}, && (12)\\
\dot{P} &= q_1 G(I) - q_2 A - \delta P, && (13)
\end{aligned}$$

with $\Lambda = \frac{\lambda}{X}$, and where we used $\mu = V(P)$ and $\Lambda = V'(P)$ for all t.

The system may exhibit 5 different regimes corresponding to all the possible combinations between the controls A and I. In order to get a general representation of the system, we will work (as far as possible) in the $\Lambda - P$ plan. The location of the 5 regimes is determined by three regime curves (RC). From (10), with $A = \phi_3 = 0$, the first RC is the horizontal axis $\Lambda = 0$. For all $\Lambda \geq (<)0$, we have $A = (>)0$.

The curve delimiting the region where $I = hP$ from the one with $I < hP$ is:

$$u'(G(hP) - d(hP) - c(A))(G'(hP) - d'(hP)) + q_1\Lambda G'(hP) = 0, \tag{14}$$

which requires $u' + q_1\Lambda > 0$.

First consider the region where $\Lambda \geq 0$. The RC is defined for $P \geq \tilde{P}(\Leftrightarrow d' \geq G')$ by:

$$\Lambda = \frac{u'(G(hP) - d(hP))}{q_1}\Big(\frac{d'(hP)}{G'(hP)} - 1\Big) \equiv F_1(\underset{+}{hP}; \underset{-}{q_1})$$

Now consider the region where $\Lambda < 0$. For $P < \tilde{P}$, we can use the relation between Λ and A, given by (10), with $\phi_3 = 0$ and $I = hP$,

$$\Lambda = -\frac{c'(A)u'(G(hP) - d(hP) - c(A))}{q_2},$$

to get $A = A(\underset{-}{\Lambda}, \underset{+}{hP}; \underset{+}{q_2})$. Replacing in (14), the second RC is implicitly defined by:

$$u'(G(hP) - d(hP) - c(A(\Lambda, hP; q_2)))(G'(hP) - d'(hP)) + q_1\Lambda G'(hP) = 0.$$

>From the implicit function theorem, we obtain:

$$\Lambda = F_1(\underset{+}{hP}; \underset{+}{q_1}, \underset{-}{q_2}).$$

This part of the regime curve joins the second part at $P = \tilde{P}$, where $\Lambda = 0$. We also have $F_1(0) = -\frac{u'(G(0)-c((c')^{-1}(\frac{q_2}{q_1})))}{q_1} < 0$, which requires $G(0) > c((c')^{-1}(\frac{q_2}{q_1}))$.

The curve delimiting the region where $I = 0$ from the one where $I > 0$ is given, from (11) with $\phi_1 = \phi_2 = 0$ and $I = 0$, by

$$\kappa\psi'(hP) = -G'(0)(u'(G(0) - c(A)) + q_1\Lambda). \tag{15}$$

It is defined only in the region where $u' + q_1\Lambda \leq 0$, which implies $\Lambda < 0$. For $\Lambda < 0$, mitigation efforts are positive and given by (10), with $\phi_3 = 0$:

$$\Lambda = -\frac{c'(A)u'(G(0) - c(A))}{q_2}. \tag{16}$$

This expression gives A as a function of Λ, parameterized by q_2: $A = A(\underset{-}{\Lambda}; \underset{+}{q_2})$. Note that imposing $\Lambda \leq -\frac{u'}{q_1}$ is equivalent to $c'(A) \geq \frac{q_2}{q_1} \Leftrightarrow A \geq (c')^{-1}(\frac{q_2}{q_1})$.

Replacing this expression in (15), we obtain the third RC in the $\Lambda - P$ plan:

$$P = \frac{1}{h}(\psi')^{-1}[-\frac{G'(0)}{\kappa}(u'(G(0) - c(A(\Lambda; q_2)) + q_1\Lambda)] \Leftrightarrow \Lambda = F_2(\underset{-}{hP}; \underset{-}{q_1}, \underset{+}{q_2}).$$

Note that the RC, F_1 and F_2, start from the same point, i.e., $F_1(0) = F_2(0)$. For the corner regime with $I = 0$ to be attainable, one must have $G(0) > c((c')^{-1}(\frac{q_2}{q_1}))$.

In sum, for any $\Lambda \geq \max\{0, F_1(P)\}$, the regime is $A = 0$, $I = hP$. For $P \geq \tilde{P}$ and $\Lambda \in [0, F_1(P))$, the regime is $A = 0$, $I \in (0, hP)$. For $P < \tilde{P}$ and $\Lambda \in [F_1(P), 0)$, the regime is $A > 0$, $I = hP$. For $\Lambda \leq F_2(P)$, the regime is $A > 0$ and $I = 0$ and for $\Lambda \in (F_2(P), \min\{F_1(P), 0\})$, the regime is $A > 0$, $I \in (0, hP)$.

B Steady state analysis

First notice that the regime with $A = I = 0$ neither hosts a steady state nor can be optimal along the transition. Suppose that there exists a non-degenerate interval of time M during which the system lies in this regime. Then, from the NOC at any $t \in M$:

$$\begin{aligned}&\Lambda = \tfrac{\phi_3}{q_2 X}\\ &\phi_1 = -X\left[u'(G(0))G'(0) + \kappa\psi'(hP) + q_1 G'(0)\Lambda\right].\end{aligned}$$

Thus, it must hold that $\Lambda \geq 0$, which in turn implies the RHS of the second equation is strictly negative, a contradiction. We can also establish that there is no steady state with $A = 0$ and $I < hP$. Suppose that such a steady state exists. Then, one must have from (10) and (12): $\Lambda = -\frac{\kappa h\psi'}{\rho+\delta} < 0$ because $\psi' > 0$, and $\Lambda = \frac{\phi_3}{q_2 X} \geq 0$ because ϕ_3 is the Lagrange multiplier associated with $A \geq 0$; another contradiction. So 3 regimes only may have a steady state: two corner regimes (with $A > 0$, $I = 0$, and with $A = 0$ and $I = hP$) and the interior regime $A > 0$, $I \in (0, hP)$.

B.1 Corner regime with $A > 0$ & $I = 0$

In this regime, a steady state solves the following system of steady state curves (SC):

$$\begin{aligned}&\Lambda = -\tfrac{\kappa h\psi'(hP)}{\rho+\delta}\\ &\delta P = q_1 G(0) - q_2 A(\Lambda; q_2) \Leftrightarrow \Lambda = \Lambda(\underset{+}{P}; \underset{-}{q_1}, \underset{+}{q_2})\end{aligned} \tag{17}$$

where the expression of A comes from (16). From the properties of the SCs, there always exists a unique intersection between them. We can further identify three necessary conditions for this steady state to be located in the right domain. The first one, mentioned above, requires that: *(i)* $G(0) > c((c')^{-1}(\frac{q_2}{q_1}))$. In addition, the second SC must start from a level below $F_2(0)$, which yields: *(ii)* $G(0) > \frac{q_2}{q_1}(c')^{-1}(\frac{q_2}{q_1})$. Finally, there must be some mitigation levels (or some Λ) for which the first SC is located below the frontier F_2. A necessary condition for this is: *(iii)* $G'(0) > \frac{\rho+\delta}{hq_1}$.

Comparative statics: combining (16) and (17), one obtains that:

$$\begin{aligned}&A^* = A(\rho, \kappa, \delta, q_1, q_2, h) \text{ with } A_\rho, A_\delta < 0;\ A_\kappa, A_{q_1}, A_h > 0;\ A_{q_2} \lesseqgtr 0,\\ &P^* = P(\rho, \kappa, \delta, q_1, q_2, h) \text{ with } P_\rho, A_{q_1} > 0;\ A_\kappa, A_h, A_{q_2} < 0;\ A_\delta \lesseqgtr 0.\end{aligned}$$

Finally, if the steady state exists, it is a saddle point. Moreover, we have $\dot{\Lambda} \geq (<) 0 \Leftrightarrow \Lambda \geq (<) -\frac{\kappa h\psi'(hP)}{\rho+\delta}$ and $\dot{P} \geq (<) 0 \Leftrightarrow \Lambda \geq (<) \Lambda(\underset{+}{P}; \underset{-}{q_1}, \underset{+}{q_2})$. The only transition possible from this regime leads the system to the interior regime with $I > 0$.

B.2 Regime with $A = 0$ & $I = hP$

If a steady state belongs to this corner regime, then it solves:

$$\begin{array}{l} q_1 G(hP) = \delta P, \\ \Lambda = \frac{hu'(G(hP)-d(hP))(G'(hP)-d'(hP))}{\rho+\delta-hq_1G'(hP)}. \end{array} \tag{18}$$

The first equation gives the unique steady state level of pollution, $P^* = \bar{P}$. By construction, it satisfies $hq_1G'(hP^*) < \delta$, which implies that $hq_1G'(hP^*) < \delta + \rho$. Now the non-negativity of Λ requires, from the second equation, that $G'(hP^*) - d'(hP^*) \geq 0 \Leftrightarrow \bar{P} \leq \tilde{P}$, which is in contradiction with the ranking considered in the main text. For any pair (P, Λ) located below the second SC, we'll have $\Lambda = 0$ in finite time because $\dot{\Lambda} < 0$. This corresponds to a switch to the regime with $A > 0$, and $I = hP$, that can only be transitory. For any (P, Λ) such that $\dot{\Lambda} > 0$, Λ keeps growing and so does P because $P < \bar{P}$. For the ranking considered, P hits $\check{P}$ then $\tilde{P}$ in finite time. Therefore from the date when $\tilde{P}$ is hit on, we have: $\frac{\dot{\Lambda}}{\Lambda} = \rho + \delta - hq_1G'(hP) + h\frac{d'(hP)-G'(hP)}{\Lambda} > \rho$. Λ grows at a rate always larger than ρ, thereby violating the transversality condition: $\lim_{t\to\infty} e^{-\rho t}\Lambda(t)P(t) = 0$.

B.3 Interior regime: $A > 0$, $I \in (0, hP)$

Here we have two controls and a state variable and it is simpler to study existence in the $A - P$ plan once we observe that (10) and (11) define a relationship $P = \Phi(I, A)$, with

$$\Phi(I, A) = \frac{1}{h}[I + (\psi')^{-1}(-\frac{u'(G(I) - c(A) - d(I))(G'(I)(1 - \frac{q_1}{q_2}c'(A)) - d'(I))}{\kappa})], \tag{19}$$

provided that the pair (I, A) satisfies $G'(I)(1 - \frac{q_1}{q_2}c'(A)) - d'(I) \leq 0$. We have

$$\begin{array}{l} \Phi_I = -\frac{u''(G'-d')(G'(1-\frac{q_1}{q_2}c')-d')+u'(G''(1-\frac{q_1}{q_2}c')-d'')-\kappa\psi''}{\kappa h\psi''} > 0, \\ \Phi_A = \frac{u''c'(G'(1-\frac{q_1}{q_2}c')-d')+\frac{q_1}{q_2}G'c''u'}{\kappa h\psi''} > 0, \end{array} \tag{20}$$

the sign of $\Phi_I > 0$ resulting from the concavity of the optimization program w.r.t I.

Combining (12), (13) and (19), the SCs in the $A - I$ plan are given by:

$$\begin{array}{l} (\rho + \delta)c'(A) + hq_2\big(G'(I)(1 - \frac{q_1}{q_2}c'(A)) - d'(I)\big) = 0 \\ q_1G(I) - q_2A - \delta\Phi(I, A) = 0. \end{array} \tag{21}$$

Note that the first equation in (21) defines the steady state curve $\dot{\Lambda} = 0$, or $\dot{A} = 0$ whereas the second corresponds to the locus $\dot{P} = 0$, as seen from $A - I$ plan. Of course we have that $\dot{A} = 0$ together with $\dot{P} = 0$ imply $\dot{I} = 0$. Note also that we work with the ranking $\check{P} < \tilde{P} < \bar{P}$, which once rewritten in terms of I, gives $\check{I} < \tilde{I} < \bar{I}$.

For all $I \geq \tilde{I}$, $d'(I) \geq G'(I)$. Define $\hat{I}$ such that $G'(\hat{I}) = \frac{\rho+\delta}{hq_1}$. For all $I \geq \hat{I} = G'^{-1}(\frac{\rho+\delta}{hq_1})$, $G'(I) \leq \frac{\rho+\delta}{hq_1}$. By construction, we have $\hat{I} < \check{I}$. A necessary and sufficient condition for the existence of a solution $A_1(I)$ to the first SC above is $I \in [0, \hat{I}] \cup [\tilde{I}, \bar{I}]$. Then we have:

$$A_1(I) = c'^{-1}\left(\frac{hq_2\big(d'(I) - G'(I)\big)}{\rho + \delta - hq_1 G'(I)}\right). \tag{22}$$

with $A_1(0) > c'^{-1}(\frac{q_2}{q_1})$, $A_1(\hat{I}) = \infty$, $A_1(\tilde{I}) = 0$. The derivative of A_1 is:

$$A_1'(I) = -\frac{hq_2(G''(I)(1 - \frac{q_1}{q_2}c'(A)) - d''(I))}{c''(A)(\rho + \delta - hq_1 G'(I))}.$$

Next, define $\check{I} > \tilde{I}$ such that $\rho + \delta = hq_1 d'(\check{I})$; then $A_1(\check{I}) = c'^{-1}(\frac{q_2}{q_1})$ and $A_1'(I) > 0$ on $[\tilde{I}, \check{I}]$. For $I \in [0, \hat{I})$, we only know that A_1 should end up being increasing as $A_1(\hat{I}) = \infty$.

The second SC can be rewritten as

$$\kappa\psi'\big(\frac{h(q_1 G(I) - q_2 A) - \delta I}{\delta}\big) + u'(G(I) - c(A) - d(I))(G'(1 - \frac{q_1}{q_2}c') - d') = 0.$$

It defines a second relationship between A and I, $A_2(I)$, with

$$A_2'(I) = \frac{q_1 G'(I) - \delta\Phi_I(I, A)}{q_2 + \delta\Phi_A(I, A)}. \tag{23}$$

To avoid discussing multiple cases (which would in any case be easy to handle), we take $\check{I} < \bar{I}$ and first search for a steady state for $I \in [\tilde{I}, \check{I}]$. One can check that $A_2(\tilde{I}) \in (0, \infty)$. If $A_2(\tilde{I}) < c'^{-1}(\frac{q_2}{q_1})$, then from (20) and (23), $A_2' < 0$ for $I > \tilde{I}$, which is sufficient to conclude that there exists a unique steady state. Otherwise, the condition $A_2(\check{I}) < (c')^{-1}(\frac{q_2}{q_1})$ is necessary and sufficient to reach the same conclusion.

Second there may also exists steady state(s) for $I \in [0, \hat{I})$. But it proves difficult to find the sign of $A_1'(I)$ and $A_2'(I)$ on that interval. Given that $A_2(\hat{I}) < \infty$, a sufficient condition for the existence of an odd number of steady states is: $A_2(0) > A_1(0) = c'^{-1}\left(\frac{hq_2 G'(0)}{hq_1 G'(0) - \rho - \delta}\right)$. Note that the inequality $hq_1 G'(0) > \rho + \delta$, identified as a necessary condition for the existence of a steady state in regime $A > 0$, $I = 0$, is also necessary for the existence of a steady state in the interior regime with $[0, \hat{I})$ because if $hq_1G'(0) \leq \rho + \delta$, $\hat{I}$ is simply not defined or equal to 0.

The dynamics can be expressed as a two dimensional system the $A - I$ plan. Combining (10)-(12) and the equations obtained by differentiating (10) and (11), we have

$$\dot{I} = \frac{1}{D}\left[\Phi_A((\rho+\delta)c'u' - \kappa hq_2\psi') - (c''u' - (c')^2u'')(q_1G - q_2A - \delta\Phi(I,A))\right], \tag{24}$$

$$\dot{A} = \frac{1}{D}\left[-\Phi_I((\rho+\delta)c'u' - \kappa hq_2\psi') + u''c'(G' - d')(q_1G - q_2A - \delta\Phi(I,A))\right]. \tag{25}$$

with,

$$\begin{aligned} &D = u''c'(G'-d')\Phi_A - \Phi_I(c''u' - (c')^2u'') \\ &= \tfrac{1}{k\kappa\psi''}[c''u'u''(G'-d')^2 + (c''u' - (c')^2u'')(u'(G''(1 - \tfrac{q_1}{q_2}c') - d'') - \kappa\psi'')], \end{aligned}$$

for $I < \tilde{I}$, D is negative; otherwise $D < 0$ if $1 - \frac{q_1}{q_2}c' \geq 0$.

Linearizing the system (24)-(25) around a steady state, we get the Jacobian matrix and the associated characteristic polynomial $P(X) = (J_1 - X)(J_4 - X) - J_2J_3 = X^2 - (J_1 + J_4)X + J_1J_4 - J_2J_3$, with

$$\begin{aligned} &J_1 = -\tfrac{1}{D}\left[c'u''(G'-d')(q_2 + \delta\Phi_A) + \Phi_Ic''u'((\rho+\delta) - hq_1G')\right], \\ &J_2 = \tfrac{1}{D}\left[c'u''(G'-d')(q_1G' - \delta\Phi_I) - \Phi_Ihq_2u'(G''(1 - \tfrac{q_1}{q_2}c') - d'')\right], \\ &J_3 = \tfrac{1}{D}\left[\Phi_Ac''u'((\rho+\delta) - hq_1G') + (c''u' - (c')^2u'')(q_2 + \delta\Phi_A)\right], \\ &J_4 = \tfrac{1}{D}\left[\Phi_Ahq_2u'(G''(1 - \tfrac{q_1}{q_2}c') - d'') - (c''u' - (c')^2u'')(q_1G' - \delta\Phi_I)\right]. \end{aligned}$$

The determinant of the Jacobian, $J_1J_4 - J_2J_3$, is equal to:

$$\det(J) = -\frac{1}{D}c''u'(q_2 + \delta\Phi_A)((\rho+\delta) - hq_1G')(A_2' - A_1'). \tag{26}$$

>From all the analysis above, we can conclude the following. At the "high" interior steady state (with $I > \tilde{I} > \hat{I}$), we have $A_2' < A_1'$, $\det(J)$ is negative and the steady state is a saddle point. As to the low steady state(s), with $I < \hat{I}$, things are more tricky. Assume that such a steady state is unique. Then, the intersection between the two SCs necessarily satisfies $A_2' < A_1'$, which now implies that $\det(J) > 0$.

C Dynamic analysis in the $\Lambda - P$ plan

To go deeper into the dynamic analysis, we take u linear and $c(A) = cA^2/2$. In this case the expression of the 2 RC reduces to:

$$F_1(P) = \frac{1}{q_1}\left(\frac{d'(hP)}{G'(hP)} - 1\right) \text{ and } F_2(P) = -\frac{1}{q_1}\left(\frac{\kappa\psi'(hP)}{G'(0)} + 1\right). \tag{27}$$

For $P \in [0, \bar{P}]$, we have: $F_1' > 0$, $F_1(0) = F_2(0) = -\frac{1}{q_1}$, $F_1(\tilde{P}) = 0$, and $F_2' < 0$.

C.1 Corner regimes with $I = hP$

Assume first that $A > 0$, and $\Lambda < 0$, Then, the SC are given by:

$$\begin{array}{l} \dot{\Lambda} = 0 \Leftrightarrow \Lambda = S_1(P) = \frac{h(G'(hP) - d'(hP))}{\rho + \delta - hq_1 G'(hP)} \\ \dot{P} = 0 \Leftrightarrow \Lambda = S_2(P) = -\frac{c}{q_2^2}\left(q_1 G(hP) - \delta P\right). \end{array}$$

Properties of $S_1(P)$: For $P \in [0, \hat{P})$, it's easy to see that $S_1(P) < F_1(P)$. So, the SC is not located in the right domain. This implies that for all $\Lambda \in (F_1(P), 0)$, $\dot{\Lambda} < 0$. For $P \in (\hat{P}, \tilde{P}]$: $S_1(\hat{P}) = +\infty$, $S_1(\tilde{P}) = 0$ and $S_1' < 0$. Again the SC is not located in the right domain; for all $F_1(P) < \Lambda < 0$, $S_1(P) > \Lambda$, which is equivalent to $\dot{\Lambda} < 0$.

Properties of $S_2(P)$: $S_2(0) = -\frac{cq_1 G(0)}{q_2^2} < 0$ and $S_2(0) < -\frac{1}{q_1} \Leftrightarrow G(0) > \frac{q_2^2}{cq_1^2}$. This is the necessary existence condition *(i)* (see the Appendix B.1), which is supposed to hold. $S_2(\bar{P}) = 0$ and $S_2(\tilde{P}) < 0$ as $\tilde{P} < \bar{P}$. $S_2' \leq 0$ for all $P \leq \check{P}$, then $S_2' > 0$. It is clear that $S_2(P) < F_1(P)$ for all $P \leq \tilde{P}$, so the second SC is not located in the right domain as well. For all $\Lambda \in (F_1(P), 0)$, we necessarily have $\dot{P} > 0$.

Consider next the regime with $A = 0$, and $\Lambda > 0$, the SCs are:

$$\dot{\Lambda} = 0 \Leftrightarrow \Lambda = S_1(P);\ \dot{P} = 0 \Leftrightarrow q_1 G(hP) = \delta P.$$

The first SC is the same as in the previous case. So we have, for $P \in [0, \hat{P})$, $\Lambda > 0 > S_1(P) \Leftrightarrow \dot{\Lambda} < 0$. And for $P \in (\hat{P}, \tilde{P}]$, $\Lambda \lesseqgtr S_1(P) \Leftrightarrow \dot{\Lambda} \lesseqgtr 0$. The second SC is a vertical line at $P = \bar{P}$. Thus, for all $P < \bar{P}$, $\dot{P} > 0$.

C.2 Regime with $A > 0$ $I = 0$, $\Lambda < 0$

The SCs are given by(17), where the second one reduces to:

$$\dot{P} = 0 \Leftrightarrow \Lambda = S_4(P) = -\frac{c}{q_2^2}\left(q_1 G(0) - \delta P\right),$$

for $q_1 G(0) - \delta P \geq 0$. $S_3(P)$ is such that $S_3(0) = 0$, $S_3'(P) < 0$ for all P. $S_4(0) = S_2(0) < -\frac{1}{q_1}$ under the same condition as before, $S_4' > 0$, and $S_4(\frac{q_1 G(0)}{\delta}) = 0$. Moreover, under Assumption 3, there exists a unique positive and finite intersection between S_3 and F_2 at: $P = \frac{1}{h}(\psi')^{-1}(\frac{(\rho+\delta)G'(0)}{\kappa(hq_1 G'(0)-(\rho+\delta))})$. The resulting level of the shadow price follows when replacing P with the expression above in either S_3, or F_2. An intersection between S_4 and F_2 also arises at P implicitly defined by:

$$\frac{c(q_1 G(0) - \delta P)}{q_2^2} = \frac{1}{q_1}\Big(\frac{\kappa\psi'(hP)}{G'(0)} + 1\Big). \tag{28}$$

Finally, it's easy to check that $\dot{\Lambda} \lesseqqgtr 0 \Leftrightarrow \Lambda \lesseqqgtr S_3(P)$ and $\dot{P} \lesseqqgtr 0 \Leftrightarrow \Lambda \lesseqqgtr S_4(P)$.

C.3 $A = 0$ $I \in (0, hP)$, $\Lambda > 0$

In this regime, the NOC (11) holds only if $I > \tilde{I}$ and allows us to define Λ as follows:

$$\Lambda = \frac{d'(I) - G'(I) - \kappa\psi'(hP - I)}{q_1 G'(I)} \equiv \xi(I, P),$$

with $\xi_I > 0$ and $\xi_P < 0$. The dynamical system is given by:

$$\begin{aligned}\dot{\Lambda} &= (\rho + \delta)\xi(I, P) + \kappa h \psi'(hP - I)\\ \dot{P} &= q_1 G(I) - \delta P\end{aligned}$$

As Λ must be positive, we necessarily have $\dot{\Lambda} > 0$. The second equation defines a SC:

$$I = (G)^{-1}(\frac{\delta P}{q_1}) \equiv I(P), \text{ with } I'(P) > 0.$$

In the $\Lambda - P$ plan, this curve is represented by the upward slowing locus obtained through the following substitution: $\Lambda = \xi(I(P), P) \equiv \tilde{\xi}(P)$ with $\tilde{\xi}'(P) = \xi_I I'(P) + \xi_P > 0$. For any pair $(P, \tilde{\xi}(P))$, i.e., located on this locus, consider an increase in Λ such that $\Lambda > \tilde{\xi}(P)$. For P given, this increase necessarily comes from an increase in I (as $\xi_I > 0$), which implies that $I > I(P)$. Then, from the differential equation in P above, it must hold that $\dot{P} > 0$. Conversely, $\Lambda < \tilde{\xi}(P) \Leftrightarrow \dot{P} < 0$.

C.4 $A > 0$ $I \in (0, hP)$, $\Lambda < 0$

The dynamics of Λ and P can be written as (with a slight abuse of notation):

$$\begin{aligned} \dot{\Lambda} &= -(\rho+\delta)\tfrac{cA}{q_2} - h(G'(I)(1-\tfrac{cq_1A}{q_2}) - d'(I)), \\ \dot{P} &= q_1G(I) - q_2A - \delta\Phi(I,A). \end{aligned} \tag{29}$$

Remind that the SCs can be studied in the $A-I$ and are given by: $A = A_1(I)$ and $A = A_2(I)$. Again we analyze the two cases ($I < \hat{I}$ vs $I > \tilde{I}$) separately.

For $I \in [\tilde{I}, \breve{I}]$: $A_1' > 0$, varying between $A_1(\tilde{I}) = 0$ and $A_1(\breve{I}) = \frac{q_2}{q_1c}$. We can take the inverse of this function, which yields $I = I_1(A)$, with $I_1' = \frac{1}{A_1'} > 0$ and $A \in [0, \frac{q_2}{q_1c}]$. As A varies in this interval, Λ belongs to $[-\frac{1}{q_1}, 0]$ because, from (10), we have $\Lambda = -\frac{cA}{q_2}$. So we ultimately obtain I as a function of Λ. We also have $A_2(\tilde{I}) \in (0, \infty)$ and $A_2(\breve{I}) \in (0, \frac{q_2}{q_1c})$, from the existence condition. Let's further assume that $A_2(\tilde{I}) > \frac{q_2}{q_1c}$ (the analysis extends easily to the opposite case). Then we can define I^ν such that $A_2(I^\nu) = \frac{q_2}{q_1c}$. On the interval $[I^\nu, \breve{I}]$, $A_2' < 0$ and we can take the inverse of A_2 to obtain: $I = I_2(A)$, with $I_2'(A) < 0$ and $A \in [A_2(\breve{I}), \frac{q_2}{q_1c}] \Leftrightarrow \Lambda \in [-\frac{1}{q_1}, -cA_2(\breve{I})/q_2]$.

Next we can use the relationship $P = \Phi(I, A)$ to express the SCs in the $\Lambda - P$ plan:

$$\begin{aligned} P &= \Phi(I_1(A), A) = P_1(\Lambda) \text{ (for } \dot{\Lambda} = 0), \\ P &= \Phi(I_2(A), A) = P_2(\Lambda) \text{ (for } \dot{P} = 0). \end{aligned}$$

As to the behavior of these two curves, we get $P_1'(\Lambda) = (\Phi_A + \Phi_I I_1')A'(\Lambda) < 0$ because $A'(\Lambda) = -\frac{q_2}{c} < 0$ and all the other derivatives are positive. And

$$\begin{aligned} &P_1(-\tfrac{1}{q_1}) = \Phi(\breve{I}, \tfrac{q_2}{q_1c}) = \tfrac{1}{h}[\breve{I} + (\psi')^{-1}(\tfrac{\rho+\delta}{\kappa h q_1})] > \breve{P} = \breve{I}/h \\ &P_1(0) = \Phi(\tilde{I}, 0) = \tilde{P}, \end{aligned}$$

and we observe that this SC is connected with the one of the regime $A = 0$, $I = hP$ at $(\Lambda, P) = (0, \tilde{P})$ because $\Lambda = F_1(\tilde{P}) = 0$.

The second SC derivative is: $P_2'(\Lambda) = (\Phi_A + \Phi_I I_2')A'(\Lambda)$. Using the expression of $I_2' = \frac{1}{A_2'} = \frac{q_2+\delta\Phi_A}{q_1G'-\delta\Phi_I}$ and rearranging, we obtain $\Phi_A + \Phi_I I_2' = (\Phi_A q_1 G' + q_2\Phi_I)/(q_1G' - \delta\Phi_I) < 0$, which in turn implies $P_2'(\Lambda) > 0$. Moreover,

$$\begin{aligned} &P_2(-\tfrac{1}{q_1}) = \Phi(I^\nu, \tfrac{q_2}{q_1c}) = \tfrac{1}{h}[I^\nu + (\psi')^{-1}(d'(I^*))] > \tilde{P}, \\ &P_2(-cA_2(\breve{I})/q_2) = \Phi(\breve{I}, A_2(\breve{I}))\tfrac{1}{h}[\breve{I} + (\psi')^{-1}(\tfrac{\rho+\delta}{\kappa h q_1} - G'(\breve{I})(1 - \tfrac{cq_1A_2(\breve{I})}{q_2}))] > \breve{P}. \end{aligned}$$

Let's further assess the local dynamics around the unique "high" steady state (see Appendix B.3). "Linearizing" the system (29) around the steady state, we obtain:

$$\begin{aligned} d\dot{\Lambda} &= -\left(\rho+\delta-hq_1G'(I^*)\right)c''(A^*)dA - h\left(G''(I^*)(1-\tfrac{q_1c'(A^*)}{q_2}) - d''(I^*)\right)dI \\ d\dot{P} &= \left(q_1G'(I^*)-\delta\Phi_I^*\right)dI - (q_2+\delta\Phi_A^*)dA. \end{aligned}$$

Consider a variation around the steady state such that $dP > 0$ and $d\Lambda = 0$. $d\Lambda = 0 \Leftrightarrow dA = 0$, which from $dP = \Phi_I^* dI + \Phi_A^* dA$, implies $dI > 0$. $dI > 0$ with $dA = 0$ in turn implies from the second equation above and $q_1G'(I^*) - \delta\Phi_I^* < 0$ that $d\dot{P} < 0$. This is enough to draw the arrows yielding the direction of changes in P within the four quadrants delimited by the SCs. Now consider a variation such that $dP = 0$ and $d\Lambda > 0$. $d\Lambda > 0 \Leftrightarrow dA < 0$ and from $dP = \Phi_I^* dI + \Phi_A^* dA = 0$, we have $dI = -\frac{\Phi_A^*}{\Phi_I^*}dA > 0$. Replacing dI with this expression in the first equation above, we obtain: $d\dot{\Lambda} = -\left[\left(\rho+\delta-hq_1G'(I^*)\right)c''(A^*)dA - h\frac{\Phi_A^*}{\Phi_I^*}\left(G''(I^*)(1-\frac{q_1c'(A^*)}{q_2}) - d''(I^*)\right)dI\right]dA > 0$, which is again enough to draw the arrows representing changes in Λ.

For $I \in [0, \hat{I})$: A_1 and A_2 are non-monotone in general. In Appendix B.3, we gave a sufficient condition for the existence of a steady state ($A_2(0) > A_1(0)$). What we can check at least is that the SCs of the interior solution, for a low I, are connected to the ones of the corner regime $A > 0$ and $I = 0$, this connection occurring on $F_2(P)$. Let us define $I_i^m = \min\{I / A_i'(I) = 0\}$ for $i = 1, 2$ (of course, I_i^m is not defined when A_i is monotone, but in this case we have no problem). Then, the reasoning developed above works when restricting our attention to the subintervals $[0, I_i^m]$, and we can express the SCs, in this region, as follows: for $\Lambda \in [\min\{\frac{cA_i(0)}{q_2}, \frac{cA_i(I_i^m)}{q_2}\}, \max\{\frac{cA_i(0)}{q_2}, \frac{cA_i(I_i^m)}{q_2}\}]$,

$$P = \Phi(I_1(A), A) = P_1(\Lambda).$$

In particular we have: $P_1(-\frac{cA_1(0)}{q_2}) = \Phi(0, A_1(0)) = \frac{1}{h}(\psi')^{-1}(\frac{(\rho+\delta)G'(0)}{\kappa(hq_1G'(0)-(\rho+\delta))})$. If the SC P_1 hits the RC F_2 at $(\Lambda, P) = (-\frac{cA_1(0)}{q_2}, P_1(-\frac{cA_1(0)}{q_2}))$, then it must hold that $-\frac{cA_1(0)}{q_2} = F_2(P_1(-\frac{cA_1(0)}{q_2})) = -\frac{1}{q_1}[\frac{\kappa}{G'(0)}\psi'(P_1(-\frac{cA_1(0)}{q_2})) + 1]$. After straightforward manipulations, we can check that this is indeed the case. We also have: $P_2(-\frac{cA_2(0)}{q_2}) = \Phi(0, A_2(0))$, and it is easy to verify that P_2 hits the RC F_2 at $(\Lambda, P) = (-\frac{cA_2(0)}{q_2}, P_2(-\frac{cA_2(0)}{q_2}))$. One can also check that $P_2(-\frac{cA_2(0)}{q_2})$ solves eq (28) (see the Appendix C.2), which is enough to conclude.

We can finally check that, for the example, the trace of the Jacobian matrix is equal to $\rho > 0$. So if there exists a unique "low" steady state, it is a source.