Confronting climate change: Adaptation vs. migration strategies in Small Island Developing States

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Abstract

This paper examines the optimal adaptation to climate change by SIDS. First we provide anecdotal and empirical support to the assumption that SIDS have two main adaptation solutions: migration and infrastructure provision. Then, we model a dynamic problem that incorporates the following ingredients. Changes in the population size, and related size of the population of emigrants, are only driven by migration decisions. Emigrants send remittances back home. Local production uses labor and the natural capital, which is degraded as a result of climate change. Investing in infrastructure is a mean to slow down this process. Solving for the intertemporal optimization program, we show that there exist two mutually exclusive development paths with different features. The first one has only the migration policy operative, and the dynamical system brings the SIDS to a state in which natural assets are seriously degraded and population is low. Along the second path, the government implements both adaptation policies. In the end, the SIDS manages to stabilize natural assets to a constant and higher level than in the former case. As a result, the population size is larger. We identify a critical condition on the fundamentals that determines which path is optimal, and discuss our results.

Keywords: SIDS, climate change, migration, natural capital, infrastructure.

JEL classification: Q54, Q56, F22.

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1 Introduction

SIDS have two important characteristics. First they are not responsible of the ongoing warming in temperatures and have no means to directly stamp it out. Second, they are the most exposed to its repercussions (Klöck and Nunn, 2019; Nurse et al., 2014).[1] The cost of inaction toward climate change will be tremoundous in these countries (UN-OHRLLS, 2017).[2] However, according to the Intergovernmental Panel on Climate Change (IPCC), these countries have no other option but to rely on adaptation measures in order to cope with climate change. Among these measures, the two main forms of adaptation are the investment in protective infrastructure (sea walls or dykes, and water treatment etc.), and population migration.

In this paper, we develop a dynamic model to assess the optimal adaptation policy of SIDS facing climate change and thus degradation of their natural asset. The policy maker which maximizes a (instantaneous) social welfare function, has two means to adapt to climate change. On the one hand, it can conduct policies that foster migration to deal with climate change, but migration induces a social cost. On the other, it may choose to slow the degradation of natural asset by building protective infrastructure. Therefore, we try to ansr to this question: how to use adaptation and migration options to manage the impacts of climate change?

Considering migration as a form of adaptation deserves further discussion. Usually, in the migration literature there is a key distinction between voluntary migration and forced migration (or displacement). Voluntary migration decision is driven by many factors, including socio-economic, cultural, and institutional ones. On the contrary, forced migration means that people do not have enough resources for subsistence. In this paper, we adopt an intermediate perspective by considering that the displacement of people as a result of the worsening of living conditions can be more than a last resort option and actually constitutes a deliberate strategy. People may indeed be willing to leave their is-

[1]See Table 1

[2]http://unohrlls.org/custom-content/uploads/2017/09/SIDS-In-Numbers_Updated-Climate-Change-Edition-2017.pdf

lands not only to get better living opportunities, but also in anticipation of future climate damages.[3] This voluntary but climate-induced migration in turn can help the inhabitants of SIDS to better adapt to climate change: if some people leave then the pressure on natural resources decreases, and those people who migrate maintain contact with their family and can bring financial support through remittances.

In SIDS, migration is an important process in the demographic features and has a large economic impact. Using data from the World bank's World Development Indicators (WDI) as well as the Trends in international migrant stock from the United Nations, Department of Economic and Social Affairs, Population Division (POP/MIG), we present three figures. In Figure 1, we represent the migrant ratio over the total population in the domestic country. It appears that SIDS' migration rate is larger than in the other countries, especially if SIDS are compared to other developing states. Secondly we show that migration from SIDS is characterized by a higher voluntary component compared to other developing states. To build this figure we compute the ratio of the refugees to the sum of the migrants stock and the refugees that live abroad (denoted $CLOS_i$). Then, we define the voluntary migration weight of a country i as the difference: $1 - CLOS_i$.[4,5] Finally, in the Figure 3, we can see that remittances – *i.e.* the transfers from the diaspora – represent on average almost 7% of the GDP in SIDS, a number which is 25% more than in the remittances in the other developing states. Therefore, the economic determinants of migration in the SIDS, are more likely to impact the level of emigration including in a context of climate change.

[3]This is different from observing that if living conditions become so degraded as a result of climate change, then they will be forced to leave (last resort option).

[4]The precise methodolgy is given in Appendix

[5]The number of migrants from a country i is defined as the sum of the people born in country i who lives in any country j. This information is observed in the destination countries.

Figure 1: Ratio of the migrants stock over the domestic population of the origin country

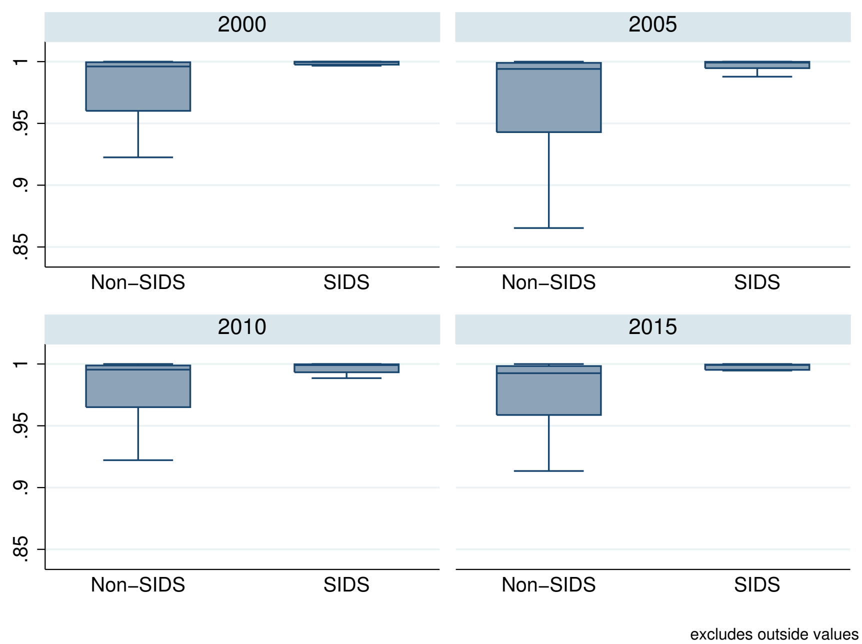

Figure 2: Ratio of refugees over the total migrant stock for developing sending countries

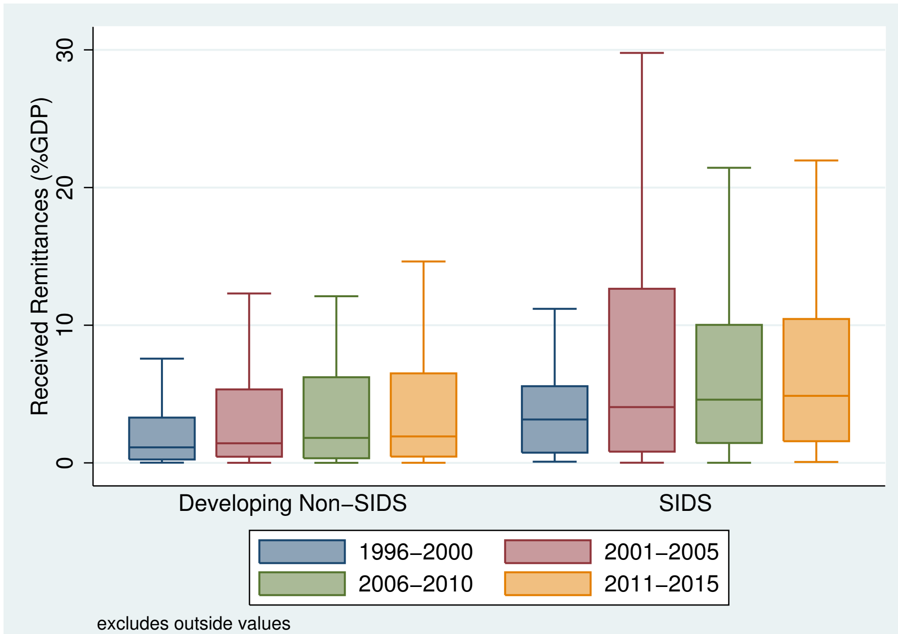

Figure 3: Remittances received in percentage of GDP (5 years average)

Moreover, there are anecdotal evidence of the use of migration as an adaptation strategy. Governments in SIDS now seriously consider the opportunity to accompany this migration process, especially in small Pacific islands which are the incarnation of the migration as an adaptation strategy. For example, the "Migration with dignity" program by the Kiribati government imply to increase the investments in public education and schooling in order to increase the attractivity of their population for receiving countries.[6] More generally, migration strategies imply to increase the emigrants' chances of economic and social integration in destination countries.

In this paper, we take these ingredients all together to assess the optimal adaption policy of SIDS facing climate change. Since both climate change and the adaption process encompass a temporal dimension, we develop a dynamic framework in which the policy maker has two means to adapt to climate change. On the one hand, it can conduct policies that foster migration to deal with the degradation of natural assets that results

[6] http://www.climate.gov.ki/category/action/relocation/

from the incurred warming. On the other, it may choose to slow this process by building protective infrastructure. The (instantaneous) social welfare function on which is based the policy-mix relies on total utilitarianism (the decision maker cares of total utility) but also incorporates a damage or a cost of migration. Changes in the size of the population in the SIDS, and consequently the size of the population of people originating from this SIDS but leaving abroad, are entirely determined by the rate of emigration. This in turn affects the economic conditions on the island through several channels that are related to the two sources of income of the SIDS. First, local production of the final good uses labor and natural capital. This implies that a sustained migration policy induces a contraction of the output because of a decreasing labor force. However, as local population decreases, the population of emigrants increases, which is associated with more remittances received. In the line with the evidence, remittances are large enough to involve a real trade-off in the management of the population. Finally, any change in the population impacts welfare directly and by changing the amount of per capita consumption. It is also a mean to release the pressure on natural assets.

To fully understand the implications of this basic trade-off, we first consider a benchmark situation in which there is no climate change, and consequently no incentive to invest in infrastructure. For an interesting problem, we consider that initial population is large enough. Then, we show that the development process displays an active migration policy, the rate of migration being monotonically decreasing, that only ends asymptotically, when the optimal size of the population is reached. Next, we examine the situation where the SIDS suffers from the impacts of climate change and can adapt to them solely by adjusting its population size. Here, the continuous degradation of natural assets induces the government to conduct a more aggressive migration policy, which results in a lower population size in the long run. This is the optimal way to adapt to the degraded (and lowest level of the) environment. Finally, we analyze the general case where both adaption policies – migration and infrastructure provision – are available tools for the decision maker. In this situation, our results point to the existence of two different development processes. In the first one, the government relies on the migration policy only and then the SIDS's dynamics are identical to the ones discussed just before. They lead the SIDS to a state in which natural assets are seriously degraded as a result of climate change and the population is low to adapt this degradation. Along the second development process, the government now chooses to implement both adaptation policies. Infrastructure expenditure are set to an initially high level and decrease monotonically, and so does the emigration rate. In the end, the SIDS manages to stabilize natural assets to a constant and higher level than in the former case. As a result, the population size is also larger in the long run. But it is a priori unclear whether per capita consumption increases or decreases. Both development processes are mutually exclusive. In fact, we identify a critical condition involving the fundamentals of the economy and the initial condition that determines which path is optimal. Based on this condition, a discussion is conducted to understand which SIDS are more likely to adopt one or the other policy. Finally, we calibrate the model in order to compare the qualitative features of the migration and population paths.

The paper is organized as follows. In Section 2, we briefly review the literature on climate change and migration. Section 3 displays the model, which is then analyzed in Section 4 and 5. Section 6 is devoted to the calibration while Section 7 concludes.

2 Related literature

2.1 The climate change damages in SIDS

A non-exhaustive list of potential impacts includes the occurrence of extreme weather events (more frequent and severe storms and hurricanes etc.), the rise in sea level accompanied by the degradation of natural capital (fresh water for consumption and agriculture, farmland and land in general because of soil erosion and intrusion of salty water), and health problems, including infectious diseases (Nurse et al., 2014). SIDS present a strong heterogeneity politically, economically, socially or culturally, however, according to the IPCC they face common constraints in terms of vulnerability and adaptation to climate change. First of all due to their high density of population, a local degradation impacts a large share of the population. Second, while the topology of these islands vary a lot according to their location or their geological formation, they all show a high concentration of their economic activities on the coastal areas. Finally, the weight of the natural assets in their economies is more likely to be high compared to other developing states. This is due to their specialization in tourism or fisheries. Therefore, even if the various climate change risks do not affect the different SIDS in the same proportion, we can identify common risks which are induced by two different types of damages, continuous ones and brutal events.

Due to the cost of potential climate change damages in the SIDS, adaptation is a prerequesite of the sustainable economic development of these countries. However, studies of the adaptation strategies in the SIDS show that the investments are far from sufficient and that they lack of coherence (Scobie, 2016; Thomas and Benjamin, 2018). Klöck and Nunn (2019) propose a literature review on SIDS adaptation to climate change. Most of the articles described in this paper focus on a region, an island or a sector (Dey et al., 2016b,a; Rosegrant et al., 2016; Valmonte-Santos et al., 2016; Weng et al., 2015; Mercer et al., 2012; Middelbeek et al., 2014; Vergara et al., 2015). They show that adaptation in SIDS is difficult to tackle because of technical and finance limits. Moreover, to the best of our knowledge, there are not works that compare two different adaptation strategies for wide impacts of climate change.

2.2 Migration as an adaptation strategy to climate change

In addition, to protective infrastructure, migration seems to be a very plausible solution for small countries. First theretical works such as Marchiori and Schumacher (2011), show that human deplacements increase if no mitigation strategies are implemented by large emitters of GHG.

According to this result, empirical papers try to predict the evolution of migration with climate change. They base their work on the past variations in human deplacements according to environmental factors such as the rainfall variability, the precipitations volume or the temperature. At a global scale, due to the complex interactions between demographic features, economic attainments and climate change effects, it is not possible to conclude that migration will be increasing in all impacted areas (Hugo, 2011). However results differ if specific regions are considered. For example, Nawrotzki et al. (2015) predicts a climate-induced increase in the international out-migration from Mexico. Thiede et al. (2016) study eight South-American countries according to the climate variability and find that depending on the region, migration is correlated to climate. Moreover, papers as Marchiori et al. (2012) or Barrios et al. (2006) find a positive correlation between weather anomalities or climate change and migration in Sub-Saharan countries. While Farbotko and Lazrus (2012), shows that they will be a cliamte induced increase in the out-migration from Tuvalu, an island of the Pacific area.

One should note that the effects of the environmental degradations on the economic results are not taken into account nor the investments, consequently, these works fail to take into account the other available optimization strategies, and thus the trade-off faced by the inhabitants in order to adapt. On the contrary, Lilleor and den Broeck (2011) introduce a first interaction between climate change and economic attainments in an economy, and secondly the demographic response to this interaction. In this paper, they find a positive correlation between the loss of revenue due to climate change and migration, but no effects from the income variability due to the increasing weather variability.

Finally, in a third group of papers, the authors introduce economic gains from migration. On one hand, migration could enhance the investments in infrastructure. Indeed, if some areas face environmental degradation, a population decrease could lead to a diminution of the environmental pressures. Therefore, economic growth per capita could be strengthened thanks to migration and/or remittances (Birk and Rasmussen, 2014). For the SIDS, Julca and Paddison (2010) or Hugo (2011) study the migration response especially through the impact of remittances in a normative approach. The first conclude, that migration or remittances could be helpful, while raising the issue of dependence to remittances, for these economies. The latter find that the sending areas will experiment many different economic, demographic and social adjustments that are difficult to anticipate. On the other hand, thanks to an empirical analysis, Ng'ang'a et al. (2016) concludes that remittances can be used to fund adaptation and thus to relax the capital constraint in the domestic county. In that case, there is a complementarity between local adaptation and migration. On the other hand it is possible to have a substituability between migration and adaptation by the infrastructure or the technology of production. Indeed, if the inhabitants leave the area the other adaptation strategies can be lessened. Barnett and Adger (2003) shows for example that the question of the habitability of two atolls depends strongly on the perception of the inhabitants towards these islands. Abandonment of these territories is more likely to occur if migration is already high because it could result in a decrease in aids and foreign investments.

2.3 The interaction between migration and the public policies

There is a wide literature on migration from the perspective of the sending countries. On the one hand, some works try to define the determinants of migration.[7] On the other hand, some works focus on the effect of migration on the sending economies – and thus on economic growth, labor markets, domestic wages, etc. In this literature, most of the migration effects transit through remittances, return migration or network. This literature is divided between the pessimistic views – that plead that there is a risk of brain drain or dependance to remittances – and the optimistic views – which support the idea that brain gain or remittances can enhance economic growth. The paper of Taylor (1999) describes precisely the arguments of these two groups.

In our work the focus is on a growing literature on the use or the control of migration as a tool for development. This is supported by international organizations such as the World Bank, the United Nations or more specifically by the International Organization for Migration (IOM) (Agunias and Newland, 2012, Clemens, 2017).[8]. There are examples of the use of migration as a policy. In the 1980s and the 1990s, many Asian countries have implemented macro-economic policies that incorporate directly labour-migration in their plan to enhance economic growth. Moreover, these policies were often accompanied

[7]see by Lilleor and den Broeck (2011) for a review of this literature

[8]http://publications.iom.int/system/files/pdf/mecc_outlook.pdf

by specific measures in order to increase the remittances flows and the repatriation or foreign earnings (Athukorala, 1993a,b).

More generally, since the 1990s the diaspora strategy is studied as a new policy tool in political geography, however most of the works were based on small-scale comparison or qualitative results. The paper of Ragazzi (2014) is one of the first work that compares in a broad analysis the attitude of the sending countries towards migration or their diaspora. In Pedroza and Palop-García (2017), they build an index of emigration policies for the Latin American and Caribbean countries. To do so they use the means implemented to ease the diaspora's lives in the destination countries. These first papers propose a positive analysis of the migration as policy, but there is also a growing literature on the diaspora strategy towards development, in a normative approach. De Haas (2010) pleads, that migration in a self-implemented phenomenon by the individuals could be inefficient. Therefore, increases in the migration gains could be obtained thanks to public transnational policies based on coordination and cooperation with the diaspora (Agunias and Newland, 2012; De Haas, 2010; Faist, 2008; Mullings, 2012).

3 Model

Let $c(t)$ be the per capita consumption at instant t, in a population of size $N(t)$. We assume away population growth and consider that any change in the population size is the result of migration, with $m(t) \geqq 0$, the emigration rate. Welfare is measured thanks to the total utility criterion, $N(t)U(c(t))$, and we also incorporate a social damage from migration, $D(m(t))$. The damage from migration covers both the cost of migration for emigrants, which are typically linked to the cultural differences, travel distance, and immigration policy in the destination country, and the cost faced by people in the origin country (loss of connections with family or friends). Function $U(.)$ is increasing and concave, and $D(.)$ is increasing and convex.

This damage function can be interpreted into two different ways. First, the lost labour effect described in the early literature on migration implies that for high level of migration, the damages due to the loss of labor may be increasing (Harris and Todaro, 1970; Lewis, 1954; Todaro, 1969). Indeed, in addition of the direct effect of the reduction of the labor size, a decrease in the productivity of the other production factors can occur (Berry and Soligo, 1969; Rivera-Batiz, 1982). Secondly, this damage function can be interpreted as an opportunity cost induced by the departures of the most skilled workers. Indeed, the loss of these agents could reduce the domestic human capital externalities or the knowledge spillovers (Basu and Weil, 1998; Jaffe et al., 1993; Keller, 2000).

The small island economy has an income made of two components. It produces the final good using a CRS technology defined over natural capital, $K(t)$, and labor, $N(t)$: the output $Y(t) = F(K(t), N(t))$, with $F_i > 0, F_{ii} < 0$ for $i = K, N$. It also receives remittances, $R(M(t))$, that financial transfers from the population $M(t)$ of migrants, i.e., of people originating from the island and who left the island in the past and settled in a foreign country. Remittances are supposed to be increasing and concave w.r.t. the stock of emigrants.

Climate impacts show themselves in the degradation of the stock of natural asset, at a constant rate $\delta > 0$, which can be slowed down by investing in specific infrastructure, $s(t)$, at cost $G(s(t))$ (increasing and convex). The natural asset corresponds to the area of available and productive land, or the reserves in fresh water that are both affected by climate change. Then, investments in infrastructure include dikes, water treatment systems etc. For simplicity, we consider infrastructure as a flow variable only. Let $\varepsilon(s(t))$ be the returns on these investments (decreasing, with $\varepsilon(0) = 1$). The law of motion of $K(t)$ is given by: $\dot{K}(t) = -\delta\varepsilon(s(t))K(t) + \delta K_\infty$. In the absence of climate change, K would remain constant. Under ongoing climate change but without public investment in protection devices, K would decrease exponentially at rate δ, going asymptotically to a positive (though potentially very low) value K_∞.

Finally, we account for the fact that the government affects migration flows directly through public policies (education and investment in human capital, investment in health infrastructure etc.). Rather than modeling explicitly the education sector of the health system, we make a shortcut by assuming that public authorities directly choose the number of emigrants.[9] In the end, the government has two instruments and seeks to reach the following objective:

$$\max_{\{s(t),m(t)\}} \int_{t=0}^{\infty} \left(N(t)U(c(t)) - D(m(t))\right) e^{-\rho t} dt$$

s.t.

$$\begin{cases} c(t) = \frac{F(K(t),N(t))+R(M(t))-G(s(t))}{N(t)}, \\ \dot{N}(t) = -m(t), \ \dot{M}(t) = +m(t), \\ \dot{K}(t) = -\delta\varepsilon(s(t))K(t) + \delta K_\infty, \\ K(0) = \overline{K}, \ N(0) = N_0, \ \text{and } M(0) = 0 \text{ given.} \end{cases}$$

with $\rho > 0$ the rate of pure time preference.

Hereafter we proceed as follows. First we define and study two benchmark scenarios: the first one depicts the situation where there is no climate impacts, which allows us to focus in the drivers of the migration policy. Next, we incorporate climate impacts but get rid of the investment in infrastructure in order to examine how the migration policy is affected by climate change. Finally, we turn to the analysis of the general case, with climate change and public spending in protective infrastructure. All proofs are gathered in the Appendix.

4 Optimal migration policy

4.1 In the absence of climate change

We start with the simplest scenario in order to describe the drivers of the migration decision and resulting outcome in terms of development. Let us then take $K(t) = K(0)$ for all t, with $K(0) = K_0$ given. This implies that there is no incentive to undertake

[9] The assumption is made for simplicity and conveys the idea that governments in SIDS can ultimately control the decision to migrate. The alternative would have consist in modeling the accumulation of human capital thanks to public education and defining the share of the population that leaves the island at every period as a function of the stock of human capital (and possibly other variables). This would have complicated the tremendously without bringing much to the analysis.

investment in protective infrastructure, $s(t) = 0$ for all t. Noticing that $M(t) = M(0) + N(0) - N(t)$ for all t, the optimization program simplifies to a one-state×one-control variable problem. The Lagrangian:

$$\mathcal{L} = N(t)U\left(\frac{F(K_0, N(t)) + R(N_0 - N(t))}{N(t)}\right) - D(m) - \lambda_N m + \mu_m m$$

with λ_N the co-state variable, and $\mu_m \geq 0$, the Lagrange multiplier.

The FOCs are given by:

$$\begin{cases} D'(m) + \lambda_N \geq 0, \ m(D'(m) + \lambda_N) = 0 \\ \dot{\lambda}_N = \rho\lambda_N - (U(c) + NU'(c)c'(N)), \\ \dot{N} = -m. \end{cases}$$

where $c(N)$ is a compact notation for the level of consumption per capita, that depends solely on N in the first benchmark. Before going any further, it is worth noticing that we hereafter assume the following: for given K, total wealth $W(K, N) = F(K, N) + R(N_0 - N)$ is inverted U-shaped and there exists a unique $N^*(K)$ such that $W_N(K, N^*(K)) = F_N(K, N^*(K)) - R'(N_0 - N^*(K)) = 0$. In other words, $N^*(K)$ is the size of the population that maximizes wealth for any given stock of natural capital.

Let us pay attention to the interior solution first ($m > 0$, $\mu_m = 0$). The first condition expresses the trade-off w.r.t the migration decision: $D'(m) = -\lambda_N \Leftrightarrow m = (D')^{-1}(-\lambda_N)$. Migration comes with a direct cost but also with potential future gains, through the change in the population size, that are captured by the shadow value of N. We immediately observe that for this equation to provide us with a non-negative migration rate, for a non-degenerate interval of time, this shadow value must be non-positive. In other words, any increase in the size of the population must be costly at the social level. There are three different effects associated with a change in N. First, a direct productive effect (through the impact on production). Next, a direct income effect (through the impact on remittances) and finally a direct size effect: other things equal, more people means less to consume per capita.

Straightforward manipulation of the FOCs yield the following dynamic system:

$$\begin{cases} \dot{m} = m\theta^{-1}\left(\rho + \frac{U(c(N))}{D'(m)}(1 - \sigma_u\sigma_c(N))\right), \\ \dot{N} = -m. \end{cases} \tag{1}$$

with $\theta = \frac{mD''(m)}{D'(m)}$ the elasticity of the marginal damage (w.r.t. m), $\sigma_u = \frac{cU'(c)}{U(c)} \in (0, 1)$, the elasticity of the utility function, and $\sigma_c(N) = -\frac{Nc'(N)}{c(N)}$ the elasticity of consumption w.r.t the population size. The first two expressions are positive, the third is also expected to be positive. Of course, they may be constant (then parameters) or not. For example, we can take the following specifications: $D(m) = \frac{1}{1+\theta}m^{1+\theta}$, $\theta > 0$ and $U(c) = \frac{1}{\sigma_u}c^{\sigma_u}$, $\sigma_u \in (0, 1)$. This would simplify the analysis and allow us to work with constant elasticities, except the last one.

Denote the share of labor in production by $\sigma_F \in (0, 1)$, and the elasticity of remittances w.r.t M by σ_R. We can then establish a first result.

Proposition 1

- *Suppose that*

$$\lim_{N \to N_0} R\sigma_R > F(\overline{K}, N_0)\sigma_F. \tag{2}$$

- *Then the optimal policy consists in undertaking positive migration for all $t < \infty$, and induces the dynamical system given by (4).*

- *Migration will stop eventually, which implies that the SIDS asymptotically reaches a constant level of population $\hat{N} \in (0, N_0)$, if and only if:*

$$\sigma_c(N_0) > \sigma_u^{-1}. \tag{3}$$

The first existence condition can simply be rewritten as $R'(0) > F_N(K_0, N_0)$. It means that the initial population is so large that the marginal productivity of labor is lower than the marginal income from remittances when there is no emigrants. The second condition involves the elasticities respectively of consumption (w.r.t N) and of utility (w.r.t consumption). The former has to be high enough compared to the latter for the existence of a permanent regime with $m > 0$ that ends asymptotically when the optimal level of population $\hat{N}$ such that $\sigma_c(\hat{N}) = \sigma_u^{-1}$ is reached.

Let us illustrate the dynamic behavior of the SIDS in the $N - m$ plan and discuss the features of the optimal trajectory. Let $H(N) = (D')^{-1}\left(-\frac{U(c(N))}{\rho}(1 - \sigma_u \sigma_{c(N)})\right)$ be the locus $\dot{m} = 0$. The horizontal axis divides the plan into the two possible regimes ($m \gtreqqless 0$). Starting from a positive level of migration below this locus, migration flows decrease monotonically until either $H(N)$ is hit in finite time, which would then lead to the second corner regime ($m = 0$), or it approaches asymptotically the critical level $\hat{N}$ that is such that $H(\hat{N}) = 0$ (the steady state being characterized by a migration rate m set at 0). It is easy to show that the first option cannot coincide with the optimal policy.

So the only option left is to follow a path along which both the population size and the rate of emigrants are monotonically decreasing and asymptotically and respectively approach $\hat{N}$ and 0. It is optimal for the island to send people to other regions/countries in order to not only reduce the pressure exerted on natural resources but also benefit from the external funding of the economy through remittances. This policy lasts until the cost of the policy (in terms of loss of social interaction and the break of family links) becomes too high, which happens only asymptotically. See Figure 4 for an illustration.

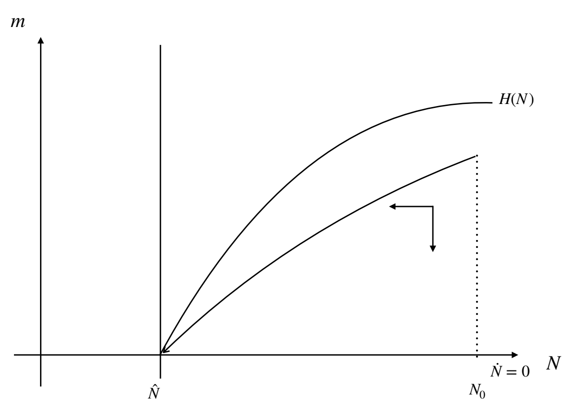

Figure 4: Optimal migration policy in the absence of climate change

4.2 Exogenous impacts of climate change

We now account for the negative impact of warming on the SIDS's natural capital. Under ongoing climate change, we in have: $K(t) = (K_0 - \overline{K}_\infty)e^{-\delta t} + \overline{K}_\infty$. The optimization program becomes non-autonomous because of the dependence of Y over $K(t)$ (still keeping $s = 0$). This problem is a straightforward generalization of the previous one. In particular, the FOCs do not change except that we have to keep track of the dependence of the dynamic system on $K(t)$ (for the interior regime with $m > 0$):

$$\begin{cases} \dot{m} = m\theta^{-1}\left(\rho + \frac{U(c(N;K(t)))}{D(m)}(1 - \sigma_u \sigma_{c(N;K(t))})\right), \\ \dot{N} = -m. \end{cases} \tag{4}$$

The general expressions of all the functions, $c(N;K)$, $\sigma_c(N;K)$, $H(N;K)$, are parameterized by K but remain unchanged, and so do their general behaviors w.r.t N. The same reasoning applies, once generalized to take into account the degradation of natural capital. This leads us to the following result (see the Appendix C).

Proposition 2 *Consider the extended version of existence conditions (2) and (3):*

$$\begin{aligned} &\lim_{N \to N_0} R\sigma_R > F(K_0, N_0)\sigma_F, \\ &\sigma_c(N, K_0) > \sigma_u^{-1}. \end{aligned} \tag{5}$$

With exogenous climate change, the region of the (N, m) plan in which it is optimal to undertake an active migration policy expands over time. In the long run, natural capital converges to its degraded stationary value, $\overline{K}_\infty$. The development path followed by the SIDS displays the same qualitative behavior during the transition as in the previous case. This means that population stabilizes to a constant level $\hat{N}(\overline{K}_\infty)$ eventually.

Asymptotically, K will converge to its lower limit $\overline{K}_\infty$, which will give the location of H: $H(N; \overline{K}_\infty)$. It intersects the horizontal axis for a level $\hat{N}(\overline{K}_\infty) < \hat{N}(K_0)(\equiv \hat{N})$. As to the shape of the optimal policy, the SIDS still settles on a path on which both m and N are positive and decreasing until the horizontal axis is hit at $N = \hat{N}(\overline{K}_\infty)$.

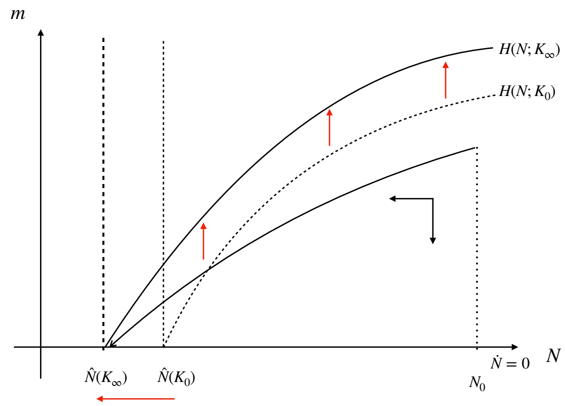

Figure 5: Optimal migration policy under exogenous climate change

Overall, the analysis of this second benchmark reveals that the optimal migration policy displays the same qualitative features as the one depicted earlier. Incorporating the (exogenous) degradation of natural capital that comes with climate change only changes the incentives to make people emigrate. Indeed, we obtain that people will keep leaving the territory even if the population gets smaller than in the first case. This logically illustrates that the optimal population size decreases in order to adapt to the much lower level of natural capital the SIDS can rest on eventually (see Figure 5).

5 Migration policy: General case

We finally analyze the general case in which the SIDS can rely on the two adaptation instruments, migration and public expenditure, in order to cope with climate change. In this situation, the two control variables may be operative and the dynamics of K is no longer exogenous. The set of optimality conditions is given by:

$$\begin{cases} D'(m) + \lambda_N \geq 0, \ m(D'(m) + \lambda_N) = 0 \\ G'(s)U'(c(N,K,s)) + \varepsilon'(s)\delta\lambda_K K \geq 0, \ s(G'(s)U'(c(N,K,s)) + \varepsilon'(s)\delta\lambda_K K) = 0 \\ \dot{\lambda}_N = \rho\lambda_N - (U(c(N,K,s)) + NU'(c(N,K,s))c_N(N,K,s)) \\ \dot{\lambda}_K = (\rho + \delta\varepsilon(s))\lambda_K - F_K(K,N)U'(c(N,K,s)) \\ \dot{N} = -m \\ \dot{K} = \delta(\overline{K}_\infty - \varepsilon(s)K) \end{cases} \tag{6}$$

with $c(N,K,s)$ the compact notation for the level of consumption per capita, $c(N,K,s) = \frac{F(K,N)+R(N_0-N)-G(s)}{N}$, and λ_K the shadow value of the stock of natural capital. The new optimality condition is the second one referring to the choice of the level of public expenditure. Assuming that the SIDS undertakes positive expenditure, then the optimal level of s is such that the marginal benefit from an increase in s, that goes through a slowing down of the deterioration of K, measured at the social value of natural capital, sets up at the level of the marginal cost of s, that takes form of a decrease in resources available for consumption thanks to an increase in the cost of providing infrastructure.

Now, the system features four different regimes depending on whether $m \gtreqless 0$ and $s \gtreqless 0$. In the previous Sections, we have seen that a regime with $m = 0$ cannot take place for a non-degenerated period on time during the transition (and can only be reached asymptotically). This means that the transitional dynamics necessarily go through either of the two following regimes: $s, m > 0$, and $m > 0$, $s = 0$.

Then the questions to address are the following: which regime can arise along the optimal solution?What are the dynamic features of these regimes? Is it possible for the economy to experience a switch from one regime to the other? We can immediately claim that switching from $s > 0$ to $s = 0$ in finite time does not make economic sense. Indeed, initial infrastructure expenditure to maintain the stock of natural capital would be wasted as the economy will end up with the lowest level of capital $\overline{K}_\infty$ eventually.

5.1 Regimes Dynamics, transition and long term outcomes

We now examine the dynamics of each regime, beginning with the situation $m > 0$, $s = 0$. This is a natural starting point because it has already been partly analyzed, i.e., in the (N, m) plan, in Section 4.2. According to (6), we have to deal with a four-dimension dynamical system that is not easy to handle in general. To overcome the difficulties, we work with projections of this system in two-dimension spaces, respectively in the plan (K, λ_K) (for $s = 0$) or (K, s) (for $s > 0$) by taking N as given, and (N, m) by taking K as given.

For simplicity, we consider hereafter the following specifications: $G(s) = \gamma s$ and $\varepsilon(s) = e^{-\eta s}$. Then for a Cobb-Douglas technology, we can define:

$$\Phi(K; N) = \frac{\eta}{\gamma}\alpha A K^{\alpha} N^{1-\alpha} - 1,$$

Let us focus on the dynamics in the (K, λ_K) plan and discuss the possibility of regime change from $s = 0$ to $s > 0$. In the regime with $m > 0$, $s = 0$, the dynamics, as represented in the (K, λ_K) plan, are given by:

$$\begin{cases} \dot{\lambda}_K = (\rho + \delta)\lambda_K - F_K(K, N)U'(c(K, N)) \\ \dot{K} = \delta(\overline{K}_\infty - K) \end{cases} \tag{7}$$

The last element we need to characterize is the critical locus that divides the (K, λ_K) into two domains, the one with $s = 0$ and the one with $s > 0$. To do so, simply replace $s = 0$ in the second FOC of system (6), and suppose that it holds with an equality. This gives us a relation between K and λ_K: $\lambda_K = \frac{\gamma U'(c(K,N))}{\delta \eta K} \equiv \xi(K; N)$, with $\xi_K(K; N) < 0$ and $s = 0$ when $\lambda_K < \xi(K; N)$. Then we can establish that (see the Appendix D.2):

Proposition 3

- *For all N, denote the solution of $\Phi(K; N) = \frac{\rho}{\delta}$ as $\tilde{K}(N)$.*
- *The regime with no protection expenditure hosts a unique steady state with $K_\infty = \overline{K}_\infty$ and $\lambda_{K\infty}(N) = \frac{F_K(\overline{K}_\infty, N)U'(c(\overline{K}_\infty, N))}{\rho+\delta}$. The optimal trajectory leading to this*

steady state displays a monotone decreasing K and a monotone increasing λ_K. It exists if and only if the following condition is satisfied:

$$\tilde{K}(N_0) > K_0. \tag{8}$$

- *A transition from the regime with $s = 0$ to the regime with $s > 0$ cannot take place in finite time.*

There are two pieces of information that we extract from Proposition 3. First and quite logically, we obtain that along the convergence to the steady state, as natural capital depreciates, its social value increases, until the steady state is asymptotically approached (see Figures 6 and 7). However, such an optimal trajectory exists iff $\tilde{K}(N_0) > K_0$. This condition involving most of the fundamentals of the economy will turn to be crucial for that analysis of the second regime and of the optimal policy. We will come back to it later. In addition, in this regime, if permanent, the behavior of the economy, as depicted in the (N, m) plan is qualitatively the same as in the second benchmark, studied in Section 4.2. Under the conditions of Proposition 2, migration rates decrease monotonically, while the population size will asymptotically approach the level $\hat{N}(\overline{K}_\infty)$ (see Figure 5).

The other important conclusion that we can draw from the analysis (and that will be later confirmed) is that policy options available to the SIDS economy are quite simple: either the government will combine active migration policy with public expenditure from the beginning, or it will never use the second instrument and simply rely on the migration policy.

Before going any further in the discussion of the optimal policy, we move to the analysis of the second regime.

When both instruments are operative, the dynamics become:

$$\begin{cases} \dot{\lambda}_K = \left[\rho - \delta\varepsilon(s)\Phi(K;N)\right]\lambda_K \\ \dot{K} = \delta(K_\infty - \varepsilon(s)K) \end{cases} \tag{9}$$

Then, we can state that (see the Appendix D.1):

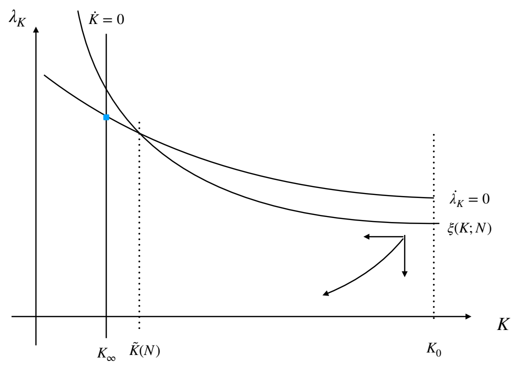

Figure 6: Dynamics in the regime $s = 0$, when $\tilde{K}(N_0) < K_0$: no optimal trajectory leading to $K = K_\infty$

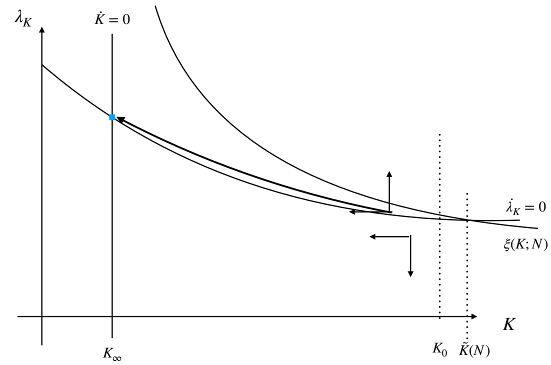

Figure 7: Dynamics in the regime $s = 0$, when $\tilde{K}(N_0) > K_0$: optimal trajectory leading to $K = K_\infty$

Proposition 4

- *The condition*

$$\tilde{K}(N_0) < K_0 \tag{10}$$

is necessary for the existence of a steady state with positive protection expenditure.

- *Suppose (10) holds. If we further impose:*

$$\begin{cases} \tilde{K}(N_0) < K_\infty, \\ \Phi(K_0; N_0) < \frac{\rho}{\delta}\frac{K_0}{\overline{K}_\infty}, \end{cases} \tag{11}$$

then there exists a unique steady state parameterized by N with $K(N) \in [\overline{K}_\infty, K_0]$, $K'(N) > 0$ and $s'(N) > 0$.

- *During the transition to the steady state, the natural capital decreases monotonically while the evolution of public expenditure may be non-monotonic.*

We immediately observe that condition (10) is just the opposite of condition (8). This is a necessary condition for the existence condition of a well-behaved solution with $s > 0$. So this ranking between $\tilde{K}(N_0)$ and K_0 drives all the results when it comes to the features

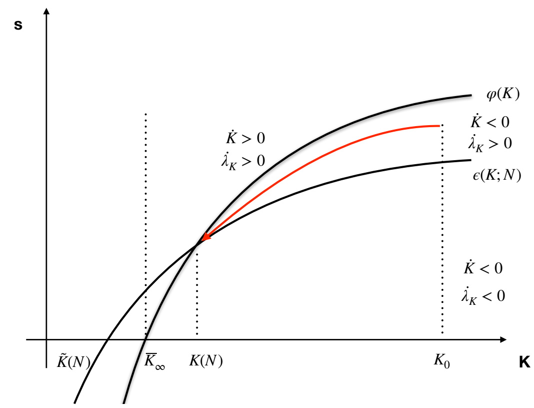

Figure 8: Optimal expenditure policy for N given

of the optimal policy. We postpone this discussion to the next Section. In the meantime, it is worth noting that other conditions are needed to ensure the existence of a steady state, in the (K, s) plan and for a given N. We observe that the lower N, the lower both s and K at the steady state. The steady state is a saddle point, and is associated with the dynamics, in the (K, s) plan, depicted on Figure 8.

As to the comparison between long run outcomes, we get:

Corollary 1 *When the SIDs economy invests in protection infrastructure, it manages to stabilize the stock of natural capital in the long run, which is compatible with a larger population size than in the absence of such expenditure.*

Not surprisingly, monitoring the speed at which natural capital deteriorates and managing to stabilize its level in the long run ultimately provides the SIDS economy with more latitude for ensuring a good enough standard of living for a larger number of inhabitants.

5.2 Optimal policy: discussion

From the analysis above, we can conclude that depending on the initial condition, and the other fundamentals of the economy, there exist two mutually exclusive development paths. Either the economy adopts a policy where it will never devote resources to protection infrastructure ($s = 0$ for all t), and only copes with the ongoing climate change by adjusting its population size thanks to migration. Or, it starts to invest in infrastructure from $t = 0$ and stick to it, while maintaining a positive level of migration. Overall, what is crucial to determine the nature of the optimal solution is the ranking between $\tilde{K}(N_0)$ and K_0: If $\tilde{K}(N_0) > K_0$, then we know that an interior steady state does not exist and the economy (should) stay(s) in the regime with $s = 0$, $m > 0$ until it asymptotically approaches the steady state with $m = 0$ (as described in Section 4.2). Otherwise $\tilde{K}(N_0) \leq K_0$, the corner steady state exist but cannot be reached, and the only option left is to settle in the interior regime until the steady state with $m = 0$ but $s > 0$ is reached. In the latter case, we expect that the economy will adopt a policy characterized by $\dot{s} < 0$.

Knowing whether $\tilde{K}(N_0) \gtreqless K_0$ deserves further discussion. First note that $\tilde{K}'(.) < 0$ and $\tilde{K}''(.) > 0$. In particular, when both N_0 are K_0 large, we expect $\tilde{K}(N_0) < K_0$, which should be associated with a trajectory with $s > 0$ and $m > 0$. On the contrary, any island featuring both a low N_0 and K_0 low should experience a development path where $s = 0$. It may seem surprising at first glance that $s = 0$ when K_0 is low enough. It however means that it is not worth preserving the natural capital when its initial level is very low. Rather, from the beginning, it is optimal to send people to some other place in anticipation of the degradation of environmental and economic conditions.

The reason for this dichotomy finds its roots in the properties of the optimal level of expenditure, $s = s(K, \lambda_K; N)$. It turns out that s is increasing in both K and λ_K, while decreasing in N. If its behavior w.r.t to λ_K is as expected, the same cannot be said of its behavior w.r.t K. But this is very intuitive after all. Indeed, the returns on public expenditure are larger the larger the stock of natural capital. In other words, it is when the stock of natural capital is high, and the negative impacts of climate change are felt the most (thanks to the exponential decrease of K), that it is worthwhile to invest a lot in protecting the natural capital. That why, in the regime with $s > 0$, expenditure follows a monotone decreasing trajectory. With the degradation of its natural capital, the SIDS progressively reduces its investments until it manages to stabilize it to a degraded, tough better than $\overline{K}_\infty$, level.

As to the comparative statics and how the location of the critical locus $\tilde{K}(N_0; \gamma, \rho, \eta, \delta, A)$ changes with the fundamentals of the economy, in the plan of initial conditions (K_0, N_0), we further obtain:

Corollary 2 $\tilde{K}_\gamma, \tilde{K}_\rho > 0$ *whereas* $\tilde{K}_\eta, \tilde{K}_\delta, \tilde{K}_A < 0$.

So, we can conclude that the larger γ and/or the lower A, the higher the cost of the infrastructure policy. In the same vein, the lower η the lower the returns on infrastructure expenditure. Finally, when ρ is high, people attach less value to what happens in the long run, while a low δ means that climate change translates into a slow degradation of the natural capital. This all points to the fact that the set of initial conditions for which it is optimal to choose $s = 0$ expands.

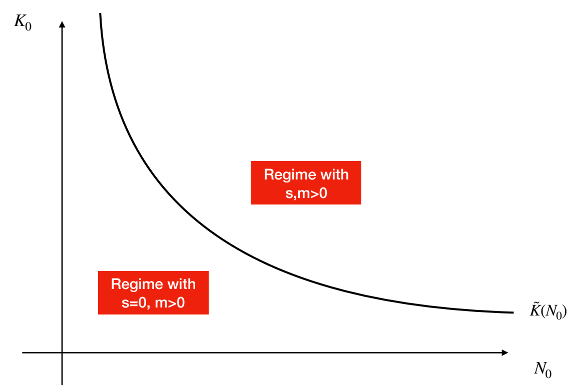

Figure 9: Separation between optimal policies in the (N_0, K_0) plan

6 Calibration

Comparison between the possible optimal trajectories: evolution of m, K and N provided by a numerical illustration.

7 Conclusion

This paper examines the optimal adaption to climate change by SIDS. First we provide anecdotal and empirical support to the assumption that SIDS have two main adaptation solutions: migration and infrastructure provision. Then, we model the dynamic problem faced by a decision maker in these regions and incorporates the following ingredients. Changes in the population size, and related size of the population of emigrants, are only driven by migration decisions. Emigrants send remittances back home. Local production uses labor and the natural capital, which is degraded as a result of climate change. Investing in infrastructure is a means to slow down this process. Solving for the decision maker's intertemporal optimization program, we show that there exist two mutually exclusive development paths with different features. In the first one, only the migration policy is operative and the dynamical system brings the SIDS to a state in which natural assets are seriously degraded and population is low. Along the second path, the government implements both adaptation policies. In the end, the SIDS manages to stabilize natural assets to a constant and higher level than in the former case. As a result, the population size is larger. We identify a critical condition involving the fundamentals of the economy, and especially the initial condition, that determines which path is optimal. Based on this condition, a discussion is conducted to understand which SIDS are more likely to adopt one or the other policy.

Possible extensions: stock of infrastructure (that would make a switch from $s > 0$ to $s = 0$ worthwhile) and indirect link between public policies and migration: discussing the timing of optimal policies.

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Appendix

A Facts

In Table 1 we present the main risks induced by climate change.

To build, the indicator of the voluntary migration in the emigration we need to correct the variable of the migrant stock in some countries. The two variables used here – *i.e.* the number of refugees and the stock of international migrants – are given respectively in the WDI and the POP/MIG datasets, however the stock of international migrants is defined in some destination countries as the sum of the voluntary migrants and the asylum

Key Risks	Continuous drivers	Risky events Drivers
Loss of livelihoods, coastal settlements, infrastructure, ecosystem services and economic stability	Warming trend – Ocean Acidification – Sea surface temperature – Sea Level Rise (SLR)	Extreme Precipitation – Damaging Cyclone
Decline and possible loss of coral reef ecosystems through thermal stress	Warming trend – Ocean Acidification – Sea surface temperature	Damaging Cyclone
Damages on low-lying coastal areas	Sea level rise – Change in the precipitation	Damaging cyclone

Table 1: Key risks with respect to the climate change drivers

Source : Authors based on Nurse et al. (2014)

seekers or the refugees. To correct this, we use the data from the United Nations High Commissioner for Refugees (UNHCR) Population Statistics Reference Database. It gives the number of refugees per destination countries. Then for the concerned countries, we subtract the number of refugees to the stock of migrants communicated. South Sudan, Djibouti, Western Sahara as well as Serbia and Kosovo are dropped from our analysis because of the incoherences between the different datasets. The international migrant stocks are given every 5 years, we use the data from 2000 to 2015 and thus the stock of refugeesin years 2000, 2005, 2010 and 2015. Therefore, the openness indicator is given by:

$$R_i = 1 - \frac{Refugees_i}{(Refugees_i + Migrants_i)}$$

B Proof of Proposition 1

The locus $\dot{m} = 0$ is defined for positive m only if there exists some N such that $1 \leq \sigma_u \sigma_{c(N)}$. Then, it yields a relationship between m and N (for $m > 0$):

$$m = H(N) \text{ with } H(N) = (D')^{-1} \left(-\frac{U(c(N))}{\rho} (1 - \sigma_u \sigma_c(N)) \right).$$

We have: $c'(N) = -\frac{1}{N^2}\left((1-\sigma_F)F(\overline{K},N) + (1+\sigma_R)R(N_0-N)\right)$, with $\sigma_F = \frac{NF_N}{F} \in (0,1)$, the share of labor in production, and $\sigma_R > 0$ the elasticity of the remittances.

Proposed specification: Cobb-Douglas technology, $Y = AK^\alpha N^{1-\alpha}$, and linear remittances, $R(M) = rM$. Then $\sigma_F = 1-\alpha$, $\sigma_R = \frac{N}{N_0-N}$, and $\sigma_R' = \frac{N_0}{N_0-N} = \frac{(1+\sigma_R)}{N_0-N} > 0$.

Using this information, we next get $\sigma_c(N) = \frac{F(1-\sigma_F)+R(1+\sigma_R)}{F+R} > 0$. The derivative of this elasticity, after some manipulations, reduces to

$$\frac{\partial \sigma_c}{\partial N} = \frac{R}{N(F+R)^2}\left(\sigma_R(1+\sigma_R)(F+R) - F(\sigma_F+\sigma_R)^2\right).$$

Now assume that $R'(0) > F_N(\overline{K},N_0)$. This is equivalent to imposing $R\sigma_R > F\sigma_F$ in the neighborhood of N_0:

$$\lim_{N\to N_0} R\sigma_R > F(\overline{K},N_0)\sigma_F. \tag{12}$$

Let us then define $\tilde{N}$ such that $R\sigma_R = F\sigma_F$. There exists an interval of variation of N, $[\tilde{N},N_0]$ such that for any N in this interval $R\sigma_R \geq F\sigma_F$. This in turn implies, from the expression above, that the elasticity of consumption will be decreasing (as N decreases) at least along all this interval.

Overall, assuming that $\sigma_u \in (0,1]$, we see that a necessary and sufficient condition for the existence of $H(N)$ is:

$$\sigma_c(N_0) > \sigma_u^{-1}. \tag{13}$$

In fact, this is also a NSC for the existence of a regime with $m > 0$. Noticing that $\sigma_c(\tilde{N}) = 1$, we can also define $\hat{N} > \tilde{N}$ such that $\sigma_c(\hat{N}) = \sigma_u^{-1}$. Of course, note that all these values are parameterized by $\overline{K}$.

The next step is to study the features of $H(N)$. We get

$$H'(N) = \frac{U\sigma_u}{\rho N D''}\left(\sigma_c(1-\sigma_u\sigma_c) + N\sigma_c'\right).$$

Note that the term between parenthesis above is decreasing in σ_u. This implies that if it is positive for $\sigma_u = 1$, it will be positive also for values lower than one. Indeed, we obtain: $H'(N)|_{\sigma_u=1}=\frac{c(N)}{\rho N D''(F+R)}\left(\sigma_F(1-\sigma_F)F\right)>0$. In sum, we get that $H(N)$ is defined for $N>\hat{N}$ with $\lim_{N\to\hat{N}} H(N)=0$, and $H'(N)\geq 0$ for all $N\in(\hat{N},N_0]$.

Starting from a positive level of migration (below this locus $H(N)$), migration flows decrease monotonically until either $H(N)$ is hit in finite time, which would then lead to the second corner regime ($m=0$), or it approaches asymptotically the critical level $\hat{N}$ at which $\dot{m}=m=0$. It is easy to show that the first option cannot coincide with the optimal policy. Suppose that there exists $T<\infty$ such that $m(T)=0 \Leftrightarrow \lambda_N(T)=0$ and $m(t)=0$, $N(t)=\bar{N}>\hat{N}$ for all $t\geq T$. Solving for the differential equation in λ_N in the corner regime, we get: $\lambda_N(t)=\frac{U(c(\bar{N})(1-\sigma_u\sigma_{c(\bar{N})})}{\rho}\left(1-e^{\rho(t-T)}\right)$. But then, the transversality condition, $\lim_{t\to\infty} e^{-\rho t}\lambda_N(t)\bar{N}=0$, cannot hold. So we get a contradiction.

C Proof of Proposition 2

In addition, we obtain: $C_K=\frac{F_K}{N}>0$, $\frac{\partial\sigma_{c(N;K)}}{\partial K}=-\frac{F_K R(\sigma_F+\sigma_R)}{(F+R)^2}<0$. Then following the same approach – and imposing the same condition(s) – as in the previous analysis, we can define $\tilde{N}(K)$ solution to $R'(N_0-N)=F_N(N,K)$, with $\tilde{N}'(K)=-\frac{F_{NK}}{F_{NN}+R''(N_0-N)}>0$ (as long as $F_{NK}>0$), and more importantly $\hat{N}(K)$ solution to $\sigma_{c(N;K)}=\sigma_u^{-1}$, with $\hat{N}'(K)=-\frac{\frac{\partial\sigma_{c(N;K)}}{\partial K}}{\frac{\partial\sigma_{c(N;K)}}{\partial N}}>0$. Finally, we can characterize the locus $\dot{m}=0$, which for positive m, is the function $H(N;K)$. Using the same trick as before, it is possible to show that the derivative of H w.r.t to K is positive: $\frac{\partial H}{\partial K}=-\frac{\sigma_u U}{\rho D''}\left(\frac{c_K}{c}(1-\sigma_u\sigma_c(N;K))-\frac{\partial\sigma_{c(N;K)}}{\partial K}\right)>0$ (evaluated in $\sigma_u=1$, the term between parenthesis simplifies to $\sigma_F>0$). To sum up, with the degradation of the stock of natural capital K, the region of the $N-m$ plan that is associated with positive migration flows expands (for any eligible N, H moves up as K decreases). This leads us to the following result.

D Proof of Propositions 3 and 4

The set of optimality conditions corresponding to the general problem is given by:

$$\begin{cases} D'(m)+\lambda_N \geq 0,\ m(D'(m)+\lambda_N)=0 \\ G'(s)U'(c(N,K,s))+\varepsilon'(s)\delta\lambda_K K \geq 0,\ s(G'(s)U'(c(N,K,s))+\varepsilon'(s)\delta\lambda_K K)=0 \\ \dot{\lambda}_N = \rho\lambda_N - (U(c(N,K,s))+NU'(c(N,K,s))c_N(N,K,s)) \\ \dot{\lambda}_K = (\rho+\delta\varepsilon(s))\lambda_K - F_K(K,N)U'(c(N,K,s)) \\ \dot{N} = -m \\ \dot{K} = \delta(K_\infty - \varepsilon(s)K) \end{cases} \tag{14}$$

with $c(N,K,s)$ the compact notation for the level of consumption per capita, $c(N,K,s) = \frac{F(K,N)+R(N_0-N)-G(s)}{N}$, and λ_K the shadow value of the stock of natural capital.

Now, the system may go through four different regimes depending on whether $m \gtreqless 0$ and $s \gtreqless 0$. In the previous Sections, we have seen that a regime with $m=0$ cannot take place for a non-degenerated period on time during the transition. Thus, regimes with $m=0$ are necessarily terminal ones.

Let us complete the analysis by reviewing the dynamic behavior of the economy in every other possible regime and associated long run outcomes. During the transition, the economy can lie in two different regimes, $s=0$, $m>0$ and $s>0$, $m>0$. We start by considering the fully interior regime. Then we will investigate the properties of the regime $s=0$, $m>0$ and assess the possibility of a regime change from $s=0$ to $s>0$. We already expect that switching from $s>0$ to $s=0$ does not make economic sense. Indeed, initial infrastructure expenditure to maintain the stock of natural capital would be wasted as the economy will end up with the lowest level of capital K_∞ eventually. This deserves a formal proof.

D.1 Regime with $s, m > 0$

D.1.1 Dynamics in the regime with $s, m > 0$

Rewriting the system of FOCs, given by (14), for an interior solution, we obtain:

$$\begin{cases} D'(m) + \lambda_N = 0 \\ G'(s)U'(c(N,K,s)) + \varepsilon'(s)\delta\lambda_K K = 0 \\ \dot{\lambda}_N = \rho\lambda_N - (U(c(N,K,s)) + NU'(c(N,K,s))c_N(c(N,K,s))) \\ \dot{\lambda}_K = (\rho + \delta\varepsilon(s))\lambda_K - F_K(K,N)U'(c(N,K,s) \\ \dot{N} = -m \\ \dot{K} = \delta(K_\infty - \varepsilon(s)K) \end{cases} \tag{15}$$

This is a four-dimension system that is not easy to handle in general. In order to get some insight, we will work with projections of the system in two-dimension spaces, respectively in the plan (K, λ_K) (for $s = 0$) or (K, s) (for $s > 0$), and (N, m).

Let us focus on the dynamics in the (K, λ_K), or (K, s), plan and discuss the possibility of regime change from $s = 0$ to $s > 0$, or the reverse. One should note that we already expect that switching from $s > 0$ to $s = 0$ does not make economic sense. Indeed, initial infrastructure expenditure to maintain the stock of natural capital would be wasted as the economy will end up with the lowest level of capital K_∞ eventually. This deserves a formal proof.

Consider the dynamics in the regime $m, s > 0$, represented in the (K, s) plan:

$$\begin{cases} \dot{\lambda}_K = \left[\rho + \delta\varepsilon(s)\left(1 + \frac{KF_K(K,N)}{G'(s)}\frac{\varepsilon'(s)}{\varepsilon(s)}\right)\right]\lambda_K \equiv \left[\rho - \delta\varepsilon(s)\phi(K,s;N)\right]\lambda_K \\ \dot{K} = \delta(K_\infty - \varepsilon(s)K) \end{cases} \tag{16}$$

where

$$\phi(K,s;N) = -\frac{\varepsilon'(s)}{\varepsilon(s)}\frac{1}{G'(s)}KF_K - 1.$$

For simplicity, we consider hereafter the following specifications: $G(s) = \gamma s$ and $\varepsilon(s) = e^{-\eta s}$. Then for a Cobb-Douglas technology, this expression reduces to:

$$\Phi(K;N) = \frac{\eta}{\gamma}\alpha AK^\alpha N^{1-\alpha} - 1,$$

with $\Phi_K = \frac{\eta}{\gamma}\alpha^2 A K^{\alpha-1} N^{1-\alpha} > 0$ for $K \in [\overline{K}_\infty, K_0]$.

We want to deal with the features of the $\dot{K} = 0$ and $\dot{\lambda}_K = 0$ loci, (from which we can infer those of $\dot{s} = 0$ locus) given that the latter is parameterized by N. This leads to the definition of two relations between s and K:

$$\begin{cases} \dot{\lambda}_K = 0 \Leftrightarrow s = \varepsilon^{-1}\left(\frac{\rho}{\delta}\Phi(K;N)^{-1}\right) \equiv \epsilon(K;N), \\ \dot{K} = 0 \Leftrightarrow s = \varepsilon^{-1}\left(\frac{K_\infty}{K}\right) \equiv \varphi(K). \end{cases} \tag{17}$$

Remember that $K \geqq \overline{K}_\infty$. Define $\underline{K}(N)$ such that $\Phi(\underline{K}(N);N) = 0$; $\underline{K}(N) = \left(\frac{\gamma}{\eta\alpha A}N^{\alpha-1}\right)^{\frac{1}{\alpha}}$, with $\underline{K}'(N) < 0$. We have $\underline{K}(N) > \underline{K}(N_0)$ for all $N < N_0$. For the first relation to exist, we must focus on the interval $[\underline{K}(N), K_0]$, which is non-empty only if the following condition holds:

$$\underline{K}(N_0) < K_0. \tag{18}$$

To be more precise, by definition $\varepsilon(s) \in [0,1]$ for $s \geq 0$, and $\varepsilon(0) = 1$. This imposes a stronger restriction on the domain of definition of K. In fact, we can define a unique $\tilde{K}(N)$ solving $\Phi(\tilde{K}(N);N) = \frac{\rho}{\delta} \Leftrightarrow \epsilon(\tilde{K}(N);N) = 0$. For the functional forms used, $\tilde{K}(N) = \left(\frac{\gamma(\rho+\delta)}{\delta\eta(1-\sigma_F)A}N^{\alpha-1}\right)^{\frac{1}{\alpha}} > \underline{K}(N)$. This means that for a solution with $s > 0$ to be well-defined, K should belong to $[\tilde{K}(N), K_0]$, which is non-empty only if $\tilde{K}(N_0) < K_0$, as $\tilde{K}(.)$ is decreasing in N. So we further impose

$$\tilde{K}(N_0) < K_0. \tag{19}$$

Remind that the stock of capital is necessarily non-increasing in our problem, so we must restrict the analysis to pairs (K,s) such that $\dot{K} \leq 0 \Leftrightarrow s \leq \varphi(K)$. The $\dot{K} = 0$ satisfies: $\varphi'(K) = \frac{1}{\varepsilon'(.)} \times -\frac{\overline{K}_\infty}{K} > 0$. For our specification we actually get $\varphi(K) = \frac{1}{\eta}\ln(\frac{K}{\overline{K}_\infty})$; thus $\varphi(\overline{K}_\infty) = \frac{1}{\eta}$, $\varphi'(K) = \frac{1}{\eta K} > 0$, and $\varphi''(K) = -\frac{1}{\eta K^2} < 0$. As to the other locus, $\epsilon'(K;N) = \frac{1}{\varepsilon'(.)} \times -\frac{\Phi_K(K;N)}{\Phi(K;N)^2} > 0$. Again, referring to the functional forms we use, we obtain $\epsilon(K;N) = \frac{1}{\eta}\ln(\frac{\delta\Phi(K;N)}{\rho})$, $\epsilon_K(K;N) = \frac{\Phi_K}{\Phi} > 0$ and $\epsilon_{KK}(K;N) = \frac{1}{\eta}\frac{\Phi_{KK}\Phi-(\phi_K)^2}{\Phi^2} < 0$. Both loci are increasing in concave in K. Given that from the second FOC in (15), $\lambda_K \geq 0$, we further have $\dot{\lambda}_K \geq 0 \Leftrightarrow s \geq \epsilon(K;N)$. We can finally observe that as N increases, so does $\epsilon(K;N)$ because $\epsilon_N(K;N) = \frac{\Phi_N}{\eta\Phi} > 0$.

Assume for now that $\varphi(K)$ and $\epsilon(K;N)$ have a unique intersection. By construction, this steady state belongs to the $\dot{s}=0$ locus, which is more difficult to study. By differentiating the second FOC in (15), that defines the optimal s as $s=s(K,N,\lambda_K)$, we get

$$\left(\frac{\varepsilon''(s)}{\varepsilon'(s)}-\frac{cU''(c)}{U'(c)}\frac{c_s}{c}\right)ds=-\left(1-\frac{cU''(c)}{U'(c)}\frac{Kc_K}{c}\right)\frac{dK}{K}-\frac{d\lambda_K}{\lambda_K},$$

noticing that $\frac{\varepsilon''(s)}{\varepsilon'(s)}=-\eta$, $-\frac{cU''(c)}{U'(c)}=1-\sigma_u$ and using the specifications, this expressions simplifies to:

$$ds=\left(\eta+\frac{\gamma(1-\sigma_u)}{Nc}\right)^{-1}\left[\left(1+\frac{Kc_K(1-\sigma_u)}{Nc}\right)\frac{dK}{K}+\frac{d\lambda_K}{\lambda_K}\right], \tag{20}$$

which means that $s_K>0$, $s_{\lambda_K}>0$ and $s_N<0$. From that, we get information about the sign of $\dot{s}$ depending on whether $\dot{\lambda}_K \gtreqless 0$ (and given that $\dot{K}\leq 0$).

We next have to determine how these two loci situate w.r.t each other. A direct comparison yields $\varphi(K)>\epsilon(K;N)\Leftrightarrow K>K(N)$, with $K(N)$ the steady state level of capital for each N (see the next Section for its characterization). The economy must satisfy $\dot{K}\leq 0$ whereas λ_K can move either way. Note however that $\dot{K}\leq 0$ and $\dot{\lambda}_K\leq 0$, with one strict inequality, together imply $\dot{s}<0$, which cannot yield the optimal trajectory. When $\dot{K}\leq 0$ and $\dot{\lambda}_K>0$, both cases are possible knowing that the optimal path is associated with a decreasing s.

A complete dynamic analysis of this regime we would finally require to switch to the second subspace and deal with the dynamics in the (N,λ_N) when $s>0$, by manipulating the first and third FOCs in (15) for any given pair (s,K). This would clearly be a cumbersome exercise. We then postpone this analysis to the calibration where we will have to verify that there is no fundamental change compared to the situation where $s=0$ (examined in the Appendix C).

D.1.2 Steady state in the regime with $s,m>0$

We know that our economy can potentially end up in two regimes: $s=0$, $m=0$, or $s>0$, $m=0$. The former case has already been discussed in the Appendix C. So let us concentrate on the latter and look at the conditions for the existence of a steady state (StS) for K and s. Using the same notations as before, a StS solves:

$$\begin{cases} \sigma_c(N,K,s) = \sigma_u^{-1} \\ K\varepsilon(s) = K_\infty \\ \rho = -\delta\varepsilon(s)(1 + \frac{KF_K}{G'(s)}\frac{\varepsilon'(s)}{\varepsilon(s)}) \end{cases} \tag{21}$$

First, we solve the system composed of of the two last equations in (K,s) to obtain their solutions expressed as a function of N. Next, we use the first equation to define N in terms of (K,s). Finally, we combine the two intermediate steps to get the existence (uniqueness) result for the StS.

Let us first study the system composed of the last two equations in (21).We search for a $K(N) \in [\tilde{K}(N), K_0]$ that solves $\varphi(K) = \epsilon(K;N)$, for any N. This is equivalent to finding the solution to: $\frac{\rho}{\delta}\frac{K}{\overline{K}_\infty} = \Phi(K;N)$. We have $\Phi_K > 0$ and $\Phi(\tilde{K}(N), N) = \frac{\rho}{\delta} < \frac{\rho}{\delta}\frac{\tilde{K}(N)}{\overline{K}_\infty} \Leftrightarrow \tilde{K}(N) > \overline{K}_\infty$. Note that $\tilde{K}(N) > \tilde{K}(N_0)$ for all $N < N_0$. Under (19), if we impose:

$$\begin{cases} \tilde{K}(N_0) \leq \overline{K}_\infty, \\ \Phi(K_0;N_0) < \frac{\rho}{\delta}\frac{K_0}{\overline{K}_\infty}, \end{cases} \tag{22}$$

then we know that there exists a unique $K(N) \in (\tilde{K}(N), K_0)$ solving the equation above. Actually, $K(N)$ is and must be larger than $\overline{K}_\infty$: $K(N) \in (\overline{K}_\infty, K_0)$. In addition, $K'(N) > 0$ as $\Phi_N(K;N) > 0$. In the end, we also obtain s as function of N, $s(N)$, simply by replacing K with $K(N)$ in for instance $\varphi(K)$, with $s'(N) = \varphi'(K)K'(N) > 0$.

Let us now assess the local stability conditions, for N given: linearizing the dynamical system (16) around the StS and using (20), we obtain the Jacobian matrix, J:

$$J = \begin{pmatrix} \delta\varepsilon(s)\left[\eta\left(\eta + \frac{\gamma(1-\sigma_u)}{Nc}\right)^{-1}\left(1 + \frac{Kc_K(1-\sigma_u)}{Nc}\right) - 1\right] & \delta\varepsilon(s)\frac{\eta K}{\lambda_K}\left(\eta + \frac{\gamma(1-\sigma_u)}{Nc}\right)^{-1} \\ \delta\varepsilon(s)\lambda_K\left[\frac{\eta\Phi}{K}\left(\eta + \frac{\gamma(1-\sigma_u)}{Nc}\right)^{-1}\left(1 + \frac{Kc_K(1-\sigma_u)}{Nc}\right) - \Phi_K\right] & \delta\varepsilon(s)\left(\eta + \frac{\gamma(1-\sigma_u)}{Nc}\right)^{-1} \end{pmatrix}$$

Direct calculations yield:

$$\det J = \eta(\delta\varepsilon(s))^2\left(\eta + \frac{\gamma(1-\sigma_u)}{Nc}\right)^{-1} K\left(\Phi_K - \frac{\rho}{\delta\overline{K}_\infty}\right).$$

Saddle point stability requires $\det J < 0$, which holds at the StS.

In the second step of the resolution, we move to the first equation in (21). Following the same lines as the analysis in the Appendices B and C. We have to deal with the properties of $\sigma_c(N,K,s) = \frac{F(K,N)(1-\sigma_F)+R(N_0-N)(1+\sigma_R)-G(s)}{F+R-G}$, especially by showing how it changes in response to a variation in K and s. Note that as $G < F + R$, the numerator of σ_c $(= -Nc_N)$ is positive if $R\sigma_R - F\sigma_F > 0$. This condition is just the same as (12), and we keep assuming that it holds in the neighborhood of N_0. We can in turn define $\tilde{N}(K)$ such that $R\sigma_R = F\sigma_F$. On the interval $[\tilde{N}(K), N_0]$, $R\sigma_R \geq F\sigma_F$. We search for the existence of a StS on the interval $[\tilde{N}(K), N_0]$. We can compute:

$$\begin{cases} \frac{\partial \sigma_c}{\partial N} = -\frac{(\sigma_F F_N + \sigma_R R' - R\sigma_R')(F+R-G)+(F_N-R')(R\sigma_R - F\sigma_F)}{(F+R-G)^2} > -\frac{\sigma_F F_N + \sigma_R R' - R\sigma_R'}{(F+R-G)^2}, \\ \frac{\partial \sigma_c}{\partial K} = \frac{-F_K R(\sigma_F+\sigma_R)+\sigma_F F_K G(s)}{(F+R-G)^2} < \frac{F_K(F\sigma_F - R\sigma_R)}{(F+R-G)^2}, \\ \frac{\partial \sigma_c}{\partial s} = \frac{G'(s)(R\sigma_R - \sigma_F F)}{(F+R-G)^2}. \end{cases}$$

Using $G < F + R$, and condition (12), and noticing that for our specifications $\sigma_F F_N + \sigma_R R' - R\sigma_R' = \sigma_F F_N - r(< 0)$, it is relatively easy to check that $\frac{\partial \sigma_c}{\partial N}$ is bounded from below by a positive term. In addition, the second derivative is bounded from above by a negative term and then is negative, whereas the third is positive.

We further know that $\sigma_c(\tilde{N}(K)) = 1 < \sigma_u^{-1}$. Taking the pair (K, s) as given, a necessary and sufficient condition for the existence of a solution to the first equation in (21) is the equivalent of (13):

$$\sigma_c(N_0; K, s) > \sigma_u^{-1},$$

uniqueness then follows from $\frac{\partial \sigma_c}{\partial N} > 0$. Denote the solution of the equation above as $\hat{N}(K, s)$.

As to the features of the solution, and how it compares to the one obtained in the Appendix C, we can proceed as follows. As we pay attention to the StS, we use the relation $s = \varphi(K) \equiv s(K)$ and define the StS population size as a function of K only: $\breve{N}(K) = \hat{N}(K, s(K))$. Then, we compute

$$\breve{N}'(K) = -\frac{\left(\frac{\partial \sigma_c}{\partial K} + \frac{\partial \sigma_c}{\partial s} s'(K)\right)}{\frac{\partial \sigma_c}{\partial N}}$$

Direct manipulations give:

$$\frac{\partial \sigma_c}{\partial K} + \frac{\partial \sigma_c}{\partial s} s'(K) < -\frac{\gamma \Phi(K;N)}{\eta K (F+R-G)^2} \leq 0 \text{ for } K \geq \tilde{K}(N).$$

Thus, the numerator above is non-negative, which means that a necessary and sufficient condition for $\breve{N}'(K) > 0$ is $\frac{\partial \sigma_c}{\partial N} > 0$, which is indeed the case. There is a clear parallel to draw between the current analysis and the one conducted in the Appendix C. Indeed, we can note that the solution we get in the benchmark case with $s = 0$, denoted by $\hat{N}(K)$, can be rewritten (with slight abuse of notation) as $\hat{N}(\overline{K}_\infty, 0)$. Moreover, the solution is clearly continuous in (K, s). As $\hat{N}$ is increasing in s but decreasing in K we then conclude that $\hat{N}(K, s(K)) > \hat{N}(\overline{K}_\infty, 0)$ for $K > \overline{K}_\infty$ and $s(K) > 0$.

The final step is to replace K with $K(N)$ in $\breve{N}$, and to determine the solution to (fixed point) $N = \breve{N}(K(N))$. We know that that there is no restriction on the domain of variation of K at the StS: $K(N) \in (\overline{K}_\infty, K_0)$. Then by construction, and for $N \in (\tilde{N}(K), N_0)$, there exists a unique N^* solving $N = \breve{N}(K(N))$.

D.2 Dynamics in the regime with $m > 0$, $s = 0$ and regime change

In the regime with $m > 0$, $s = 0$, the dynamics, as represented in the (K, λ_K) plan, shrink to:

$$\begin{cases} \dot{\lambda}_K = (\rho + \delta)\lambda_K - F_K(K,N)U'(c(K,N)) \\ \dot{K} = \delta(\overline{K}_\infty - K) \end{cases} \tag{23}$$

The steady state of this regime, that has been studied in the (N, m) plan earlier, is located at the (unique) intersection between the vertical line $K = \overline{K}_\infty$ and the locus $\dot{\lambda}_K = 0$, which now defines a relation between K and λ_K, for N given: $\lambda_K = \frac{F_K(K,N)U'(c(K,N))}{\rho+\delta} \equiv \zeta(K;N)$, with $\zeta_K(K;N) = \frac{F_{KK}U'(c)+F_K c_K U''(c)}{\rho+\delta} < 0$ and $\dot{\lambda}_K \geq 0 \Leftrightarrow \lambda_K \geq \zeta(K;N)$. In addition, note that $\zeta_N(K;N) > 0$. In addition, it is quite easy to check that the steady state of the corner regime with $s = 0$ is saddle point stable. This means that convergence can occur only along the part of the stable branch originating in the domain where $\dot{\lambda}_K > 0$ and $\dot{K} < 0$. This makes sense: as natural capital depreciates, its social value increases during the transition to the StS.

Now, the last pending question is, is a transition from $s = 0$ to $s > 0$ possible in finite time? To answer this question, we have to define the critical locus, or frontier, that divides the (K, λ_K) into two domains. To do so, simply replace $s = 0$ in the second FOC of system (14), and suppose that it holds with an equality. This gives us another relation between K and λ_K: $\lambda_K = \frac{\gamma U'(c(K,N))}{\delta \eta K} \equiv \xi(K; N)$, with $\xi_K(K; N) = \frac{\gamma}{\delta \eta K^2}(K c_K U''(c) - U'(c)) < 0$ and $\xi_N(K; N) = \frac{\gamma}{\delta \eta K} c_N U''(c) > 0$. Moreover, we get that $s = 0$ when $\lambda_K < \xi(K; N)$.

The respective location of $\zeta(K; N)$ and $\xi(K; N)$ directly comes from the following comparison: $\zeta(K; N) \leq \xi(K; N) \Leftrightarrow K \leq \tilde{K}(N)$ with $\tilde{K}(N)$, the lower bound on the interval of variation of K on which we studied the existence of a steady state with $s > 0$. This means that if $\overline{K}_\infty < \tilde{K}(N_0) < K_0$, then the economy with no infrastructure expenditure must be originally located in the region with $\dot{\lambda}_K < 0$ and $\dot{K} < 0$, which is not compatible with the existence of an optimal trajectory leading to the corner steady state. In other words, $\tilde{K}(N_0) > K_0$ is a necessary and sufficient condition for the existence of a corner solution with $s_\infty = 0$. This also implies that a transition from the corner regime with $s = 0$ to the interior regime with $s > 0$ cannot take place ever.

The qualitative features of the regime with no investment in infrastructure – $s = 0$, $m > 0$ – is unchanged compared to the analysis conducted in Appendix C.

E Model specification

The functional forms used at the different stages of the analysis are the following:

- power functions with $D(m) = \frac{1}{1+\theta} m^{1+\theta}$, $\theta \geq 1$, and $U(c) = \frac{1}{\sigma_u} c^{\sigma_u}$, $\sigma_u \in (0, 1)$.
- Cobb-Douglas technology:$Y = AK^\alpha N^{1-\alpha}$, and linear remittances: $R(M) = rM$. Then $\sigma_F = 1 - \alpha$, $\sigma_R = \frac{N}{N_0 - N}$, and $\sigma'_R = \frac{N_0}{N_0 - N} = \frac{(1+\sigma_R)}{N_0 - N} > 0$.
- Linear cost of infrastructure expenditure $G(s) = \gamma s$, with $\gamma > 1$ the cost of public funds, and $\varepsilon(s) = e^{-\eta s}$.