The dynamic implications of tourism and environmental quality

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Abstract

Many studies draw attention to the rising number of tourists seeking destinations in environmental hotspots. However, it is also recognized that tourism activities significantly deteriorate the environment. Our paper investigates the dynamic interaction between tourism and environmental quality, focusing on its effect on the development of tourism-based economies. We empirically confirm this reverse causality using the example of the Caribbean. We then use a theoretical model in order to study the dynamic implications of this interaction. In this respect we identify the role of played by abatement activities and ecotourism as well as the existence of imbalance effects.

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1 Introduction

Numerous studies point out that environmental quality plays a fundamental role in attracting tourists for many economies; see, amongst others, Font, 2000; and Christ *et al.*, 2003. However visitors, and the corresponding provision of tourist services, frequently cause significant environmental degradation (May, 1995; Gossling *et al.*, 2002; and Burak *et al.*, 2004). Thus intensively promoting tourism may in turn reduce the future attractiveness of destinations located in environmental hotspots. Indeed it has long been recognized that there may be reverse causality between tourism and environmental quality (for instance, McConnell and Duff, 1976; McConnell, 1977; Tisdell, 2001; Huybers and Bennett, 2003; or Gopalakrishnan *et al.*, 2011). The aim of this paper is to explicitly study the relationship between tourism and environmental quality. Since this interaction can seriously affect the development of tourism-based economies, we pay particular attention to its dynamic implications.

A handful of theoretical papers have already studied the dynamic properties of the problem of reverse causality of tourism and environmental quality, focusing on the sustainability of tourism activities. For example, Kort *et al.* (2002) introduce a theoretical framework to analyze the investment decisions of a tourism planner. They find that this dual causality has important dynamic implications for the evolution of the environmental conditions of the economy, tourism and the subsequent investment in physical capital ("touristic infrastructures" in their paper). However, their set-up only considers a planner that maximises the (discounted stream) of touristic revenues and thus they are not able to study the social optimum, where the policy maker would also take into account households' preferences. Moreover, the abatement activities are not explicitly included as a decision variable for the planner. Following a neoclassical growth approach, Cerina (2007) provides an alternative framework and considers the social optimum where the level of abatement is amongst the decision variables. Nevertheless, the model does not explicitly incorporate physical capital, which is a key ingredient of the problem (as, for instance, in terms of infrastructure in Greiner *et al.*, 2001, and Kort *et al.*, 2002). Related papers, such as Lozano *et al.* (2005), Gómez *et al.* (2008), and Rey-Maquieira *et al.* (2009), do include physical capital investments, but only study a decentralised economy, concentrating on its long-run properties. Moreover, again abatement activities are neglected in these models.

Another important shortcoming of the aformentioned papers is that they all either simply assume or refer to secondary evidence that there is in reality actual reverse causality between tourism and environmental quality. We thus as a first task set out to empirically confirm the existence of such a relationship. To this end we consider the example of the Caribbean. Arguably, the Caribbean constitutes an ideal case study for the issue at hand. More precisely, the coastal environment and beaches of the Caribbean have made the region one of the most appealing destinations for tourists (for instance, Patullo, 1996; Sadler, 1988; Christ *et al.*, 2003).[1] However, maintaining environmental quality is particularly important for beach destinations, where the coastal environmental conditions are defining components of the value of beaches (*e.g.*, Smith *et al.*, 2009; and Beharry-Borg and Riccardo Scarpa, 2010). As a matter of fact, it has been argued that the Caribbean is typical of the trade-off between tourism and environmental quality in coastal areas; see (BfN, 1997). To explicitly test this, we compile a panel data set on environmental quality and tourism for 22 Caribbean Island destinations from 1995 until 2013. As usual in this literature, we measure the level of tourism activity of a destination (country) by means of tourist arrivals. Regarding environmental quality, we consider coastal nightlight intensity as a proxy of seashore and beach environmental degradation. In this regard, several studies, such as Amaral *et al.* (2005), Lui *et al.* (2011) and Henderson *et al.* (2012), have shown that nightlights are highly correlated with population density. It is also well-known that overcrowding is responsible for much environmental degradation of beaches, since it destroys the "naturalness" of the environment (among others, McConnell, 1977; Brau, 2008; and Oh *et al.*, 2010; Santana-Jiménez and Hernández, 2011). Moreover, overcrowding indirectly deteriorates the beach environment due to the increase of pollution and beach erosion, and the reduction of water quality (*e.g.*, Silva *et al.*, 2008; Smith *et al.*, 2009; Roca *et al.*, 2009; and Beharry-Bord and Scarpa, 2010). Taking coastal nightlight intensity as a measure of such overcrowding and its effects on environmental quality we explicitly demonstrate using Granger causality tests that there is indeed reverse causality between it and tourism arrivals.

Having empirically confirmed the actual existence of dual causality, we then proceed to use a theoretical model in order to investigate the dynamic implications of such an interaction between tourism and environmental quality. In contrast to the previous literature, we focus on the social optimum explicitly including physical capital and abatement activities. To do so, we consider a Ramsey-type model for tourism and environmental quality. Since the aim of our paper is to highlight the dynamic dimension of this interaction, we provide a stylised framework that represents a small open economy where

[1] It is well-known that the Caribbean is a highly dependent economy on tourism (amongst others, Bresson and Logossah, 2011; and Laframboise *et al.*, 2014). According to WTTC (2015), in 2014, the total contribution of tourism to the Caribbean GDP was 14.6%, with a forecast of 15.4% for 2025. This region has the highest total contribution of tourism to the GDP, which contrasts with the much lower figures for the EU and the US (9.7% and 8.2%, respectively). Tourism moreover contributes to 12.2% of the total investment of the Caribbean, while this number reduces to 4.9% for the EU and to 4.0% for the US.

tourism is the main economic activity. Tourism services are produced by means of using labour, physical capital, and environmental quality. But, at the same time, tourism activities induce environmental degradation of the economy, which will undermine the future provision of tourism and, thus, income and welfare. Differing from the standard literature on natural resources (*e.g.*, Dasgupta and Heal, 1974, 1979; Solow, 1974; and Stiglitz, 1974), instead of the extraction flow, the whole stock of natural resources (environmental quality in this paper) is considered to be a production input of the economy.

We show that, if the efficiency of abatement activities is high enough, appropriate planning of tourism can guarantee positive levels of environmental quality, GDP, and welfare in the long-term. In the context of our set-up, and consistent with the United Nations World Tourism Organization (UNWTO, 2002), we define ecotourism as a type of tourism that involves activities with low environmental impact, giving great importance to the environmental quality of the destination. We find in this respect that promoting ecotourism reinforces the sustainability result above. However, regarding the convergence, the development of the economy will be slower due to the greater attention paid to the evolution of the environmental conditions of the economy. This outcome allows us to detect a social cost of ecotourism in terms of future generations' welfare. We finally identify the possibility of an imbalance effect between physical capital and environmental quality. We show that small developing economies endowed with high environmental quality, but lacking of physical capital such as infrastructures and tourism facilities, will optimally sacrifice part of their environmental quality during the initial periods of their development. Because of the greater attention devoted to the accumulation of physical capital, the environmental conditions will temporarily deteriorate, followed by a recovery once the economy reaches a high enough level of development.

The paper is organized as follows. Section 2 provides empirical evidence of the dual causality between tourism and environmental quality. We present in Section 3 the theoretical model together with the corresponding optimal conditions. Section 4 considers the long-run behaviour of the economy, while sections 5 and 6 describe the dynamics. Finally, Section 7 concludes.

2 Empirical evidence

The aim of this section is to provide empirical evidence of the double causality between tourism and environmental quality. We first present the methodology based on the Granger causality test. After describing our panel data for the Caribbean Island destinations, we apply the procedure in order to confirm our hypothesis.

2.1 Methodology

To empirically verify the reverse causality between tourism and environmental quality we adopt a dynamic panel causality approach. More specifically we estimate a panel-based error-correction model to test for Granger causality between tourist arrivals and environmental degradation.[2] A two-step procedure is applied. In the first step we estimate a long run relationship using the panel dynamic-OLS (PDOLS) proposed by Mark and Sul (2003). This approach is robust to the presence of endogeneity and outperforms all other studied estimators, both single equation and system estimators (Wagner and Hlouskova, 2010).[3] Moreover, it is well-known that in small T samples (like in the present context) the PDOLS estimator performs better than other available estimators, like the FIML estimator of Johansen's (1988) or the fully modified ordinary least squares (FMOLS) estimator of Phillips and Hansen (1990), amongst others. To obtain the long run relationship the PDOLS relies on the following model:

$$y_{it} = \alpha_{1i}^{'} d_{it} + \beta_{1i}^{'} x_{it} + \nu_{it}, \tag{1}$$

where $i = \{1, \ldots, N\}$ represents the cross-sectional unit, $t = \{1, \ldots, T\}$ denotes the time dimension, y_{it} and x_{it} represent, respectively, the dependent variable and the vector of explanatory variables, ν_{it} denotes the estimated residuals which represent deviations from the long-run relationship, and d_{it} the vector of deterministic components. d_{it} includes individual intercepts (to capture country-specific fixed effects), a time trend (for time specific effects) and common time dummies.

To eliminate the potential endogeneity of the variables included in the vector x_{it} the PDOLS methodology, proposed by Mark and Sul (2003), estimates the following model:

$$y_{it} = \alpha_{1i}' d_{it} + \beta_{1i}' x_{it} + \delta_{1i}' z_{it} + \nu_{it}, \tag{2}$$

where $z_{it} = (\Delta x_{it-p}', \ldots, \Delta x_{it}', \ldots, \Delta x_{it+p}')'$ is a $(2p+1)k$ dimensional vector of leads and lags of the first differences of the variables x_{it}.

With the above setting in mind, we estimate the long run relationship between tourist arrivals and environmental quality by estimating:

$$V_{it} = \alpha_{1i}' d_{it} + \beta_{1i}' D_{it} + \delta_{1i}' z_{it} + \nu_{it}, \tag{3}$$

where V represents tourism arrival and D stands for environmental degradation. All other terms are defined as above.

[2]The Granger causality means that the knowledge of past values of one variable X helps to improve the forecasts of another variable Y.

[3]Endogeneity is controlled by regressing potential endogenous variables in each equation on the leads and lags of the first-differenced regressors from all equations.

In the second step, a panel-based error-correction model can be used to test for Granger-type causality between tourism arrivals and environmental degradation. To this end, in the spirit of Holtz-Eakin *et al.* (1988), we estimate an error correction model with one period lagged residuals, obtained from estimating equation (3):

$$\Delta V_{it} = \gamma_{1i} + \sum\nolimits_{p=1}^{k} \gamma_{11ip} \Delta V_{it-p} + \sum\nolimits_{p=1}^{k} \gamma_{12ip} \Delta D_{it-p} + \phi_{1i} \widehat{\nu}_{it-1} + \omega_{1it} \tag{4}$$

$$\Delta D_{it} = \gamma_{2i} + \sum\nolimits_{p=1}^{k} \gamma_{21ip} \Delta V_{it-p} + \sum\nolimits_{p=1}^{k} \gamma_{22ip} \Delta D_{it-p} + \phi_{2i} \widehat{\varepsilon}_{it-1} + \omega_{2it}, \tag{5}$$

where Δ is the first-difference operator, k is the optimal lag length (set at two),[4] $\widehat{\nu}_{it-1}$ and $\widehat{\varepsilon}_{it-1}$ are the error correction terms obtained from estimating the PDOLS estimation of equation (3).

With respect to equations (4) and (5) above one can obtain both short and long term causality. Indeed, short term causality is tested with a Wald test by imposing the restrictions $\gamma_{12ip} = 0$ in (4) and $\gamma_{21ip} = 0$ in (5). Long run causality is revealed by the statistical significance of the parameter of the error correction terms (ϕ) using a t-test. Operatively, the estimates are obtained by means of the dynamic panel method based on the General Methods of Moments (GMM).

2.2 Data

Tourism data

Our source for tourists in the Caribbean is the annual number of tourist arrivals for Caribbean countries and territories in the period 1995-2010. This data is available online from www.onecaribbean.org, which is the official tourism business website of the Caribbean Tourism Organisation. Data on tourist arrivals is available for 22 Caribbean islands: Aruba, Antigua, Antigua, Netherland Antilles, Bahamas, Belize, Bermuda, Barbados, Cuba, Dominica, Dominican Republique, Guadeloupe, Grenada, Guyana, Haiti, Jamaica, St. Kitts and Nevis, St. Lucia, Martinique, Puerto Rico, Turks and Caicos Islands. Trinidad and Tobago, St. Vincent and the Grenadines, British Virgin Islands, and US Virgin Islands.

Environmental degradation data

As noted in the introduction we use nightlight intensity in coastal areas as proxies of environmental degradation. More specifically, since the early 1970s the Defence Meteorological Satellite Program (DMSP) has produced ground-level night time imagery,

[4] For annual data it is standard practice to set the optimal lag at 2

intended to provide weather and climate data, amongst other cloud cover imagery, to improve the effectiveness of military operations. Following its declassification, the data has mostly been used for civil purposes, providing a comprehensive and continuous data set of nightlight intensity to scientists, where the digital archive of this product extends back to 1992. In the present study, we resort to data from 1995 to 2010, in correspondence with our tourist arrivals data. In terms of coverage each DMSP satellite has a 101 minute near-polar orbit at an altitude of about 800km above the surface of the earth, providing global coverage twice per day, at the same local time each day.[5] In the late 1990s, the National Oceanic and Atmospheric Administration (NOAA) developed a methodology to generate "stable, cloud-free nightlight data sets by filtering out transient light, such as produced by forest fires, and other random noise events occurring in the same place less than three times" from this raw data (see Elvidge *et al.* (1997) for a comprehensive description). Resulting images are percentages of nightlight occurrence for each pixel per year normalized across satellites to a scale ranging from 0 (no light) to 63 (maximum light). The spatial resolution of the original pictures was about 0.008 degrees on a cylindrical projection (*i.e.*, with constant areas across latitudes) and was later converted to a polyconic projection, leading to squares of about 1 km^2 near the equator. In order to get yearly values, simple averages across daily (filtered) values of grids were generated. We take the coastal areas of all our Caribbean regions and extract the nightlight cells within 1km of these. The average value for each region is then used as a measure of environmental stress.

Summary statistics

In terms of summary statistics, we first depict the tourism sector's contribution to GDP of the Caribbean islands in 1995 and 2010, in Table 1, as taken from statistics published by the World Travel & Tourism Council (WTTC). Accordingly, the importance varies considerably, ranging from 5.62 (Puerto Rico) to 73.73 (Antigua) in 1995 and 5.40 (Puerto Rico) to 79.01 (Aruba) in 2010. Moreover, for some countries tourism as a contributor to economic activity has fallen for some islands but risen for others. Overall, however, it is clear that for most tourism is of considerable importance to their economy.

The mean values of annual tourist arrivals (in '000s) and nightlight intensity, as well as the total coast length and the number of arrivals per km of coast are also given in Table 1. As can be seen, the islands differ substantially in terms of their total coast length. For instance, the Bahamas, Cuba, and Haiti have the longest coast, while St.

[5] Note that there have been so far 5 satellites covering the following sub periods: satellite n°10: 1992-1994; n°12: 1994-1997; n°14:1997-2003; n°15: 2000-2007; n°16: 2004-2009. In order to handle the data during overlapping periods, we have taken, for each cell, simple averages of nightlight values across satellites.

Vincent and the Grenadines, the British Virgin Islands and Aruba are characterized by the shortest coastline.[6] One may also want to note that both the number of arrivals and the nightlight intensity on coastal areas varies substantially in the region. In this regard, the most visited island is the Dominican Republique, with over 3 million tourist arrivals on average per year since 1995, where Puerto Rico closely follows suit with just under 3 million tourists. In contrast, Antigua, St. Kitts & Nevis, Dominica, and St. Vincent and the Grenadines are less popular tourist destinations. While the islands with less coast to offer are in general those less visited, this is not always the case. For instance, Barbados and Aruba, both with coasts of less than 35 km, are the 9th and 6th greatest tourist destinations in the Caribbean. In terms of potential coastal environmental stress, here proxied by nightlight intensity, it is even more difficult to discern any pattern in terms of coastal length. As a matter of fact, the simple correlation coefficient between these two is -0.26 and statistical insignificant. Finally, we depict in the last column the number of annual tourist arrivals by km of coast. Accordingly, Aruba, Puerto Rico, and Barbados have the largest average coastal tourist density, while figures are lowest for Antigua, the Bahamas, and Haiti. In correlating these two series we find a coefficient of 0.74, statistically significant at the 5 per cent level.

2.3 Results

Before estimating our main models two crucial conditions need to be satisfied. First, an important feature of equation (3) is the assumption that in the long-run permanent changes in V are associated with permanent changes in D. Empirically this implies the two variables must be non-stationary or integrated of the same order, although a linear combination of them might be stationary. For this reason the variables V and D are tested for unit roots using the tests developed by Levin *et al.* (2002), Im *et al.* (2003), and Pesaran (2007). While the first two tests assume cross-sectional independence, the last allows for cross-sectional dependence. Second, once the order of integration of the variables is established we test for the existence of a long run relationship between the variables V and D. To this end we resort to the tests proposed by Kao (1999), Pedroni (2004) and Westerlund (2007). The Kao (1999) and Pedroni (2004) tests assume a common factor restriction, *i.e.*, they assume that the long run parameters for the level variables are equal to the short term parameters for differenced variables, whilst the Westerlund (2007) test accounts for cross-sectional dependence.

The panel unit root tests results are presented in Table 2. The reported results in-

[6] One may want to note that we were unable to obtain any indication of what portion of the coast of any island is actually suitable for swimming etc, and thus assume by default that all coast is available for tourist recreational activity.

Table 1: Summary statistics

Isocode	% tourism to GDP (1995)	% tourism to GDP (2010)	Arrivals ('000s)	Nightlight intensity	Coast Length (km)	Arrivals/ Coastline
Aruba	48.84	79.01	707	34	69	10246
Antigua	73.12	66.65	52	13	153	339
Netherland Antilles	35.73	36.04	235	21	364	645
Bahamas	65.7	44.39	1532	6	6542	234
Bermuda	26.95	14.71	306	18	103	2970
Barbados	37.35	39.36	520	29	97	5360
Cuba	9.23	9.2	1792	8	3735	479
Dominica	20.1	28.72	72	3	148	486
Dominican Republic	16.07	14.07	3125	6	1288	2426
Guadeloupe	19.02	14.92	536	12	306	1751
Grenada	25.3	20.61	120	5	121	991
Haiti	7.33	6.64	170	6	1771	95
Jamaica	26.56	27.55	1436	9	1022	1405
St. Kitts and Nevis	31.61	22.07	97	12	135	718
St. Lucia	48.7	32.15	272	18	158	1721
Martinique	13.51	10	487	13	350	1391
Puerto Rico	5.62	5.4	2981	30	501	5950
Turks and Caicos Islands	n.a.	n.a.	161	10	389	413
Trinidad and Tobago	8.51	7.06	380	14	362	1049
St. Vincent and the Grenadines	23.43	19.62	76	5	84	904
British Virgin Islands	70.19	78.41	296	8	80	3700
US Virgin Islands	47.01	26.65	531	1	188	2824

dicate, overwhelmingly, that the null hypothesis of the unit roots for the variables V and D cannot be rejected in levels.[7] However, the null is rejected when series are in first differences. Consequently, it can be inferred from the results that both variables are integrated of order one, *i.e.*, $I(1)$. Having established the order of integration of our two variables, V and D, we test whether there is a co-integrating relationship among them. The corresponding results are portrayed in Table 3. The evidence strongly indicates the existence of a cointegrating relationship between V and D, where 11 out of the the 12 statistics reject the null hypothesis of no cointegration.[8]

Given the existence of cointegration the PDOLS is estimated in order to retrieve the residuals which are paramount in the implementation of the causality technique. The results related to the causality analysis, the main focus of the paper, are presented in Table 4. The short-run causality results reveal a positive and statistically significant causality from tourist arrivals (V) to environmental degradation (D) and a negative and statistically significant causal effect from D to V. The long run dynamics displayed by

[7]The Levin test reject the null for the variable D, albeit at the 10 percent level. However, given that the other two tests do not reject the null we conclude that the variable is $I(1)$.

[8]Only the Pedroni $Panelv - Statistics$ fails to reject the null.

Table 2: Panel unit root tests

Variable	$W-stat$	$p-value$	t^*	$p-value$	Z_{tbar}	$p-value$
V	-1.253	0.105	1.134	0.872	0.393	0.653
D	-1.124	0.131	-1.338*	0.091	3.765	1.000
ΔV	-4.357***	0.000	-2.904***	0.000	-3.527***	0.000
ΔD	-7.894***	0.000	-6.278***	0.000	-3.260***	0.001

Notes: (1) All unit-root tests are implemented with a constant and trend in the test regression and take a unit-root as the null hypothesis. (2) The lags are chosen according to the Akaike criterion. (3) The $p-values$ are for a one-sided test based on the normal distribution. (4) *,**,*** represent 10, 5, and 1 percent significance levels, respectively

Table 3: Panel cointegration tests

Kao (1999)	*Pedroni (2004)*			Westerlund (2007)
Stat	Within-dimension	Stat		Stat
-8.012***	*Panel v-stat*	-2.649	*Gt*	-3.242***
[0.000]		[0.996]		[0.000]
	Panel rho-stat	-3.219***	*Ga*	-17.38***
		[0.001]		[0.000]
	Panel pp-stat	-5.184***	*Pt*	-9.264***
		[0.000]		[0.000]
	Panel ADF-stat	-5.522***	*Pa*	-13.531***
		[0.000]		[0.000]
	Between-dimension			
	Group rho-stat	-1.816**		
		[0.035]		
	Group pp-stat	-9.064***		
		[0.000]		
	Group ADF-stat	-9.906***		
		[0.000]		

Notes: (1) [·] represent p-values; (2) **,*** reject the null of no cointegration at the 5 and 1 percent levels, respectively.

the estimates of the error correction terms reveal that V and D respond to deviations from the long-run equilibrium given the statistical significance of their respective error correction terms. Indeed, the long run results are in line with the short run causality findings. All in all, the causality results support a bidirectional causality between tourist arrivals and environmental degradation.

3 Theoretical model

As pointed out in the introduction several research and policy studies recommend taking into account the dynamic interaction between tourism and environmental quality. In particular, the literature considers that this relationship is important to analyze the

Table 4: Panel causality results

	Short-run causality		Long-run causality
	$\Delta V(-1)$	$\Delta D(-1)$	$ECT(-1)$
ΔV		-0.104**	-0.259***
		[0.0492]	
ΔD	0.197**		0.614***
	[0.100]		[0.171]

Notes: (1) Standard error in parenthesis. (2) *,**,*** represent 10, 5, and 1 percent significance levels, respectively.

sustainability of economic activity in tourism-based regions. Following this research direction, we will investigate the dynamic implications of the reverse causality empirically identified in the previous section. We introduce in this regard a Ramsey-type model of a small open economy. In this section we present the model and the corresponding optimal conditions. We will study the long-term equilibrium and the dynamic properties of the economy in the remaining parts of the paper.

Consistent with our empirical findings, let us assume an economy that provides tourism services using labour, physical capital, and environmental quality. However, at the same time, these tourism activities entail an environmental degradation of the economy, which will compromise the future provision of tourism. We consider three simplifications in order to highlight the dynamic interaction between tourism and environmental quality. First, in line with Table 1, we assume that tourism is the main source of income of the economy. We actually focus on the extreme situation where the country cannot diversify the economic activity. This is often the case with many tourism-based economies, where tourism is the only sector with a comparative advantage. Second, since in this paper we do not explicitly study the choice between quantity and quality of tourism, tourism services will be identified as tourism arrivals in our model.[9] Third, we assume as usual that the economy is small. This simplification has two main implications in our model. On the one hand, our economy will be not able to influence tourism demand. On the other hand, since the excess of tourists is the most relevant case for environmental degradation, we assume that there is always enough demand to fill the tourism services provided by the small economy. Thus the policy makers has to set the optimal number of tourism that are allowed to visit.

We consider that tourism is a composite good in accordance with the tourism economics literature (for instance, McConnell, 1977; Fleischer and Rivlin, 2008; and Rey-

[9]For further discussion about quantity *vs.* quality of tourism see, amongst others, Cower and Tabarrok (1995), Caserta and Russo (2002), and Fleischer and Rivlin (2008).

Maquieira *et al.*, 2009). In our simplified set-up:

$$T(t) = F(E(t), L(t), K(t)). \tag{6}$$

Tourism services $T(t)$ are provided by means of combining labour $L(t)$ and physical capital $K(t)$. As noted before, we also assume that the environmental quality of the economy $E(t)$ is a significant factor of attraction for tourism. Since the main source of income of our economy is tourism, we will identify income $Y(t)$ as tourism services, *i.e.*, $Y(t) = T(t)$.[10] We will consider a Cobb-Douglas technology in order to obtain a closed-form solutions:

$$F(E(t), L(t), K(t)) = AE(t)^{\alpha} L(t)^{\beta} K(t)^{\gamma}, \tag{7}$$

where $\alpha, \beta, \gamma > 0$ are the corresponding output elasticities with $\alpha + \beta + \gamma = 1$, and $A > 0$ is the scale parameter. As generally assumed in the economic growth literature, labour demand $L(t)$ equals population size $N(t)$, which is assumed to increase at an exogenous rate $n \geq 0$ with a given initial population $N(0) > 0$. The evolution of environmental quality is simply described as:

$$\dot{E}(t) = \sigma M(t) - \epsilon E(t) - \vartheta T(t). \tag{8}$$

Tourism services reduce the environmental quality of the economy, while investing in maintenance $M(t)$ improves environmental conditions. Parameters $\sigma, \vartheta > 0$ represent, respectively, the effect of those two factors on the evolution of the environmental conditions of the economy. We interprete environment quality as the environmental services required for the provision of tourism activities. In this respect, some maintenance is needed to preserve the economic value of the environment as a production factor. As in Mariani *et al.* (2010), the parameter $\epsilon \in (0, 1)$ stands for an exogenous rate of deterioration of the environment. A typical example of this phenomenon is the erosion of beaches due to exogenous elements such as ocean currents, wave action, storms, sea levels, *etc.* (see for instance, Munk and Traylor, 1947). Indeed, this type of "natural" deterioration, together with the erosive impact of tourism facilities and housing, has frequently justified the implementation of preservation policies, such as sand replenishment of beaches, commonly known as "beach nourishment" (among others, Landry and Weeler, 2003; and Gopalakrishnan *et al.*, 2011). In our simplified set-up, we additionally assumed that there is no natural regeneration of environment conditions. We will focus on this limited case because the aim of our paper is to underline the negative effect of tourism on the

[10] One could alternatively set $Y(t) = p(t)T(t)$, where $p(t)$ is the international price of tourism services. We consider a small open economy, so $p(t)$ would be taken as given. Moreover, since the explicit modelling the international tourism demand is beyond the scope of this paper, we normalize this price to one abstracting from further assumptions about its long-run trend. For an additional interpretation based on tourists' willingness to pay see, for instance, Cerina (2007) and Rey-Maquieira *et al.* (2009).

environmental conditions of the economy. Regarding physical capital we consider the law of motion:

$$\dot{K}(t) = I(t) - \delta K(t), \tag{9}$$

where $I(t)$ is investment and the parameter $\delta \in (0,1)$ represents physical capital depreciation. Finally, the resources constraint of the economy is stated as:

$$Y(t) = C(t) + I(t) + M(t). \tag{10}$$

In this paper we will focus on the social optimum. We therefore assume that the policy maker maximizes the lifetime discounted utility of the households of our economy, considering the typical temporal discount $e^{-\rho t}$, with $\rho > n$:

$$\max_{\{c,m\}} \int_0^\infty u(c(t))e^{-(\rho-n)t}dt \tag{11}$$

subject to

$$\begin{cases} \dot{k}(t) = f(e(t),k(t)) - m(t) - c(t) - (\delta+n)k(t), \\ \dot{e}(t) = \sigma m(t) - (\epsilon+n)e(t) - \vartheta f(e(t),k(t)), \\ e(0), k(0) > 0 \text{ given.} \end{cases} \tag{12}$$

Note that all the variables of the social optimum problem (11)-(12) are expressed in per-capita terms, using from now on lowercase letters. The constraints (12) are obtained by using equations (6) and (10) in (8) and (9), and then rewriting the corresponding laws of motion in per-capita units. For the Cobb-Douglas technology (7), the output per capita is $f(e(t),k(t)) = Ae(t)^\alpha k(t)^\gamma$.[11] As we observed in the introduction, in contrast to the standard literature on natural resources, our economy produces with the whole stock of natural resources (environmental quality in this paper) instead of with the extraction flow. The environmental conditions of the economy determine, together with labour and physical capital, the provision of tourism services.

The Hamiltonian of the social optimum problem takes the form:

$$\begin{aligned} H(c,m,e,k,\mu,\lambda) &= u(c(t)) + \mu(t)[\sigma m(t) - (\epsilon+n)e(t) - \vartheta f(e(t),k(t))] \\ &+\lambda(t)[f(e(t),k(t)) - m(t) - c(t) - (\delta+n)k(t)], \end{aligned} \tag{13}$$

where $\mu(t)$ and $\lambda(t)$ are, respectively, the shadow price (co-state variable) of the environmental quality and the physical capital. Taking the corresponding first order conditions (FOC) $\partial H/\partial c(t) = 0$, $\partial H/\partial m(t) = 0$, $\partial H/\partial e(t) = -\dot{\mu}(t) + (\rho-n)\mu(t)$, and $\partial H/\partial k(t) = -\dot{\lambda}(t) + (\rho-n)\lambda(t)$, we state the following proposition:

[11] Following the neoclassical assumptions for a generic production function $f(e(t),k(t))$, we consider diminishing returns, *i.e.*, $f_i' > 0$ and $f_{ii}'' < 0$, together with $\lim_{i\to\infty} f_i' = 0$ and $\lim_{i\to 0} f_i' = \infty$, for $i = \{e,k\}$.

Proposition 1. *Every solution of the problem (11)-(12) verifies*

$$\frac{\dot{c}(t)}{c(t)} = \frac{1}{\xi(c(t))}\left[\frac{(\sigma-\vartheta)}{\sigma}f'_k - (\delta+\rho)\right], \tag{14}$$

$$\dot{k}(t) = f(e(t),k(t)) - m(t) - c(t) - (\delta+n)k(t), \tag{15}$$

$$\dot{e}(t) = \sigma m(t) - (\epsilon+n)e(t) - \vartheta f(e(t),k(t)), \tag{16}$$

$$g(e(t),k(t)) = 0, \tag{17}$$

and the transversality conditions (TC)

$$\lim_{t\to\infty} e(t)\exp\left(-\int_0^t [(\sigma-\vartheta)f'_e - \epsilon - n]ds\right) = 0, \tag{18}$$

$$\lim_{t\to\infty} k(t)\exp\left(-\int_0^t [(\sigma-\vartheta)f'_e - \epsilon - n]ds\right) = 0, \tag{19}$$

where $g(e(t),k(t)) \equiv (\sigma-\vartheta)f'_e - \frac{\sigma-\vartheta}{\sigma}f'_k - (\epsilon-\delta)$, $\xi(c(t)) \equiv -\frac{u''(c(t))c(t)}{u'(c(t))}$, *and* $e(0), k(0) > 0$ *are given.*

Proof. See Appendix A. □

Equation (14) is the Euler condition of the problem, which describes the trade-off between current and future consumption. In this expression $\frac{1}{\xi(c(t))}$ represents the elasticity of intertemporal substitution. In particular, $\xi(c(t)) = 1$ for a logarithmic utility $u(c(t)) = \ln c(t)$, while it is equal to a constant $\theta \in (0,1)$ for a CRRA utility $u(c(t)) = \frac{c(t)^{1-\theta}-1}{1-\theta}$. Equations (15) and (16) are the law of motion of our state variables, *i.e.*, environmental quality and physical capital. Equation (17) establishes an important relationship between the environmental conditions and the stock of physical capital of the economy at every moment of time. We will see later on that this equation has a unique solution, allowing us to express $k(t)$ as a function of the environmental quality for every $t \geq 0$, *i.e.*, $k(t) = h(e(t))$. Hence this property will reduce the dimension of the dynamical system, simplifying the tractability of the dynamic analysis of the economy. Moreover, since the initial conditions for the environmental quality and the stock of physical capital are given, there may be the case that $k(0) \neq h(e(0))$. This will allow us to identify a possible imbalance effect between the environmental conditions and the endowment of physical capital of the economy. We investigate this possibility in Section 6. The last two expressions (18) and (19) are the transversality conditions associated with each state variable of our problem. Notice finally that the conditions in Proposition 1 are not only necessary but also sufficient. Following Seiertad and Sydsaeter (1987), and Le Kama and Schubert (2007), it is easy to prove that the maximized Hamiltonian is strictly concave for the Cobb-Douglas technology, provided that the negative impact of tourism on the environmental conditions of the economy is relatively small with respect to the efficiency of maintenance (*i.e.*, $\vartheta < \sigma$):

Proposition 2. *For* $\vartheta < \sigma$, *the necessary conditions (14)-(19) are also sufficient.*

4 Long-run behaviour

As in the standard neoclassical growth model without technical progress, we will study the steady-state. A steady-state is defined as an equilibrium path in which all variables of the problem (11)-(12) are constant for all t. This concept of long-term equilibrium is useful to understand the main mechanisms behind the interaction between tourism and environmental quality. In particular, it allows us to illustrate the possibility of sustaining a socially optimal level of tourism activities, when the environmental quality plays a significant role in the provision of these sort of services. A main difficulty comes from the fact that tourism itself deteriorates the environmental conditions of the economy. In this section we focus on the steady-state, leaving for Sctions 5 and 6 the analysis of the dynamics of the economy around this equilibrium point.

Let us consider the dynamical system (14)-(17) at the steady-state. Given the Cobb-Douglas technology (7), we can establish the following proposition that characterizes the long-run behaviour of our economy:

Proposition 3. *For $\vartheta < \sigma$, the economy has a unique steady-state $(e^*, k^*, m^*, c^*) > 0$, which is given by*

$$e^* = \left(\frac{A\alpha^{1-\gamma}\gamma^{\gamma}}{\Psi_1^{1-\gamma}\Psi_2^{\gamma}} \right)^{\frac{1}{1-\gamma-\alpha}}, \tag{20}$$

$$k^* = \frac{\Psi_1}{\Psi_2}\frac{\gamma}{\alpha}e^*, \tag{21}$$

$$m^* = \frac{1}{\sigma}[\vartheta f(e^*, k^*) + (n+\epsilon)e^*], \tag{22}$$

$$c^* = f(e^*, k^*) - m^* - (\delta + n)k^*, \tag{23}$$

where $\Psi_1 \equiv \frac{\epsilon+\rho}{\sigma-\vartheta}$, $\Psi_2 \equiv \frac{\sigma}{\sigma-\vartheta}(\delta+\rho)$, and $f(e^*, k^*) = Ae^{*\alpha}k^{*\gamma}$.

Proof. See Appendix B. □

The proposition states that the economy can sustain long-term economic activity, maintaining the compatibility between tourism and environmental quality. But it is necessary that the negative impact of tourism on the environmental conditions of the economy (ϑ) is relatively small with respect to the efficiency of maintenance (σ). One can additionally verify that, under this condition, the steady-state values e^*, k^*, y^* and c^* rise when ϑ falls.[12] In our model, the situation of lowering ϑ corresponds to an economy

[12]The net effect on m^* depends on the strength of both $\partial y^*/\partial\vartheta$ and $\partial e^*/\partial\vartheta$ (see equation 22). For instance, if the elasticity of output with respect to ϑ is greater than 1 (in absolute value) the policy maker does not need to increase much more the long-term output. So she does not keep a very high level of environmental maintenance in order to provide more tourism services and, thus, more income. Therefore, $\partial m^*/\partial\vartheta < 0$ as well.

that encourages tourism activities with reduced environmental impact. This case represents the typical example of economies promoting ecotourism. In this respect our paper is in line with studies supporting ecotourism as a valid strategy to sustain economic activity and environmental quality in tourism-based economies (among others, World Bank, 1998; and Huybers and Bennett, 2003; and UNWTO, 2012).

Proposition 3 identifies as well an interesting feature about the optimal proportion of production factors. Equation (21) shows that there is a long-term ratio between physical capital and environmental quality: $k^*/e^* = \frac{\Psi_1}{\Psi_2}\frac{\gamma}{\alpha}$. As we will show in the next section, a fixed relationship between $e(t)$ and $k(t)$ also holds along the transition path, eventually converging to this ratio. This result points out that the policy maker should ensure a balanced provision of infrastructures and tourism facilities (*i.e.*, physical capital) that is compatible with the subsequent transformation of the environmental conditions due to tourism. Therefor in tourism-based economies careful planning and management would be required to sustain a long-term level of economic activity. This statement is congruence with arguments made by international organizations, such as the World Tourism Organization, regarding in particular the tourism development in small island developing states (*e.g.*, Briguglio, 1995; van der Velde *et al.*, 2007; and UNWTO, 2012).

5 Dynamics

Let us study the local dynamic properties of the economy around the steady-state equilibrium identified above. As observed before, we will first reduce the dimension of the dynamical system (14)-(17) by means of specifying the relationship between $k(t)$ and $e(t)$ from $g(e(t), k(t)) = 0$. Applying the inverse function theorem, one can verify that there exists a unique one-to-one relationship between $k(t)$ and $e(t)$ of the form $k(t) = h(e(t))$ if $f''_{ee}f''_{kk} \neq f''_{ke}f''_{ek}$. This condition actually holds for our Cobb-Douglas technology. However, we cannot write in general $k(t) = h(e(t))$ as a closed-form expression. The implicit function theorem still allows us to conclude that $h(e(t))$ is a strictly increasing function of $e(t)$ because $f''_{ke} > 0$. Moreover, if we assume that the depreciation rate of both physical capital and environmental quality are the same, *i.e.*, $\epsilon = \delta$, it is easy to identify that $k(t) = \frac{1}{\sigma}\frac{\gamma}{\alpha}e(t)$. For $\epsilon \neq \delta$ the relationship $k(t) = h(e(t))$ cannot be explicitly written in terms of $e(t)$ and the underlying parameters. But since the focus of the paper is on the local dynamics, we can alternatively linearize $g(e(t), k(t)) = 0$ in a neighborhood of the steady-state (e^*, k^*):

Proposition 4. *Around the steady-state equilibrium*

$$k(t) = \frac{\epsilon + \rho}{\sigma(\delta + \rho)}\frac{\gamma}{\alpha}[\Phi_1 e(t) + \Phi_2 e^*], \tag{24}$$

where $\Phi_1 \equiv \frac{\alpha(\delta+\rho)+(1-\alpha)(\epsilon+\rho)}{\gamma(\epsilon+\rho)+(1-\gamma)(\delta+\rho)}$ *and* $\Phi_2 \equiv \frac{\beta(\delta-\epsilon)}{\gamma(\epsilon+\rho)+(1-\gamma)(\delta+\rho)}$.

Proof. See Appendix C. □

The optimal condition (24) allows us to reduce the dynamical system (14)-(17) to a system of two equations and two unknowns. Considering (17), the Euler condition (14) can be rewritten as

$$\frac{\dot{c}(t)}{c(t)} = \frac{1}{\xi(c(t))}[(\sigma - \vartheta)f_e' - (\epsilon + \rho)]. \tag{25}$$

If we replace $m(t)$ in (16) from (15), the law of motion of the environmental conditions becomes

$$\dot{e}(t) = (\sigma - \vartheta)f(e(t), k(t)) - \sigma c(t) - \sigma[(\delta + n)k(t) + \dot{k}(t)] - (\epsilon + n)e(t). \tag{26}$$

Applying Proposition 4 to (25) and (26), and rearranging terms, we obtain the following reduced-dimension system for $c(t)$ and $e(t)$:

$$\frac{\dot{c}(t)}{c(t)} = \frac{1}{\xi(c(t))}\left\{\alpha A(\sigma - \vartheta)\left(\frac{\epsilon+\rho}{\sigma(\delta+\rho)}\frac{\gamma}{\alpha}\right)^{\gamma} e(t)^{-(1-\alpha)}[\Phi_1 e(t) + \Phi_2 e^*]^{\gamma} - (\epsilon+\rho)\right\}, \tag{27}$$

$$\frac{\dot{e}(t)}{e(t)} = \left[1 + \frac{\gamma(\epsilon+\rho)}{\alpha(\delta+\rho)}\right]^{-1} \times$$
$$\left\{A(\sigma - \vartheta)\left(\frac{\epsilon+\rho}{\sigma(\delta+\rho)}\frac{\gamma}{\alpha}\right)^{\gamma} e(t)^{-(1-\alpha)}[\Phi_1 e(t) + \Phi_2 e^*]^{\gamma} - \sigma\frac{c(t)}{e(t)} - \frac{\gamma(\delta+n)(\epsilon+\rho)}{\alpha(\delta+\rho)}\left[\Phi_1 + \Phi_2\frac{e^*}{e(t)}\right] - (\epsilon+n)\right\}. \tag{28}$$

The equations (27) and (28), together with the transversality condition for the environmental quality, describe the optimal behaviour of our economy around the steady-state. For $\epsilon = \delta$ the system can be simpler stated because we directly know the closed-form expression of the ratio $k(t)/e(t)$. In this particular case $\Phi_1 = 1$ and $\Phi_2 = 0$. So rewriting (27) and (28) we get the system:

$$\frac{\dot{c}(t)}{c(t)} = \frac{1}{\xi(c(t))}\left\{B(\sigma - \vartheta)e(t)^{(\alpha+\gamma)-1} - (\epsilon + \rho)\right\}, \tag{29}$$

$$\frac{\dot{e}(t)}{e(t)} = B\frac{\sigma - \vartheta}{\alpha + \gamma}e(t)^{(\alpha+\gamma)-1} - \sigma\frac{\alpha}{\alpha+\gamma}\frac{c(t)}{e(t)} - (\delta + n), \tag{30}$$

where $B \equiv \alpha A(\frac{\gamma}{\alpha\sigma})^{\gamma}$.

6 Dynamic response

In order to study the optimal transitional behavior of the economy, and the corresponding stability properties of the steady-state, we will consider the reduced-dimension system identified in the previous section. For ease of exposition we will focus on the simplified problem where $\epsilon = \delta$. The detailed results for $\epsilon \neq \delta$ are reported in Appendix G.

6.1 Transitional dynamics

Let us log-linearize the dynamical system above. This will allow us to explicitly describe the dynamics of the economy and, in particular, the speed of convergence.[13] We denote by $\tilde{x}(t)$ the log of a variable $x(t)$. Rewriting (29) and (30) in logs, and taking into account that $B\frac{\sigma-\vartheta}{\alpha+\gamma}\exp\{-(1-\varphi)\tilde{e}^*\} - \frac{\alpha}{\alpha+\gamma}\sigma\exp\{\tilde{c}^*-\tilde{e}^*\} = \epsilon+n$ and $B(\sigma-\vartheta)\exp\{-(1-\varphi)\tilde{e}^*\} = \epsilon+\rho$, with $\varphi \equiv \alpha+\gamma$, we obtain the following linearized system (in matrix form) after a first-order approximation around the steady-state equilibrium described in Proposition 3:

$$\begin{bmatrix} \dot{\tilde{e}}(t) \\ \dot{\tilde{c}}(t) \end{bmatrix} = J \times \begin{bmatrix} \tilde{e}(t) \\ \tilde{c}(t) \end{bmatrix} + \begin{bmatrix} -(\rho-n)\tilde{e}^* - [(\epsilon+n) - \frac{\epsilon+\rho}{\varphi}]\tilde{c}^* \\ \frac{1}{\theta}(1-\varphi)(\epsilon+\rho)\tilde{e}^* \end{bmatrix}, \tag{31}$$

where J is the Jacobian matrix of the system, evaluated at the steady-state:

$$J \equiv \begin{bmatrix} (\rho-n) & (\epsilon+n) - \frac{\epsilon+\rho}{\varphi} \\ -\frac{1}{\theta}(1-\varphi)(\epsilon+\rho) & 0 \end{bmatrix}. \tag{32}$$

We calculate the two eigenvalues of J, which will be denoted by $\bar{\alpha}_i$ with $i = \{1, 2\}$. This will allow us to study the stability properties of the steady-state. Moreover, we will be able to provide a closed-form solution of the optimal trajectory and the corresponding speed of convergence. By solving $\det(J - \bar{\alpha}I) = 0$, we obtain:

$$\bar{\alpha}_i = \frac{1}{2}\left\{(\rho-n) \pm \sqrt{(\rho-n)^2 + \frac{4(1-\varphi)(\epsilon+\rho)}{\theta}\left[\frac{\epsilon+\rho}{\varphi} - (\epsilon+n)\right]}\right\}. \tag{33}$$

One can verify that the expression inside the square root is strictly positive because the term between the square brackets is strictly positive. Hence both eigenvalues are real. Moreover, if we denote $\bar{\alpha}_{1(2)}$ as the eigenvalue corresponding to the positive (negative) sign before the square root, we can see that $\bar{\alpha}_1 > 0$ and $\bar{\alpha}_2 < 0$.[14] We then establish the following proposition:

Proposition 5. *The Jacobian matrix of the linearized system (31) has two real eigenvalues, one positive and the other negative. Therefore, for $\epsilon = \delta$, the economy exhibits saddle-path stability (unique stable manifold).*

The property of saddle-path stability implies two important conclusions. First, the steady-state equilibrium in Proposition 3 is stable. Consequently, we can conclude that it is possible to sustain a long-term level of tourism that is compatible with the conservation of the environmental quality of the economy. But the saddle-path property of the stability also implies that the optimal trajectory is unique. Thus sustainability will require an attentive supervision by the policy maker of the provision of tourism services.

[13]We provide a qualitative analysis of the dynamics (phase diagram) in Appendix D.

[14]It is easy to see that $\det(J) < 0$. Since $\det(J) = \bar{\alpha}_1\bar{\alpha}_2$ we can conclude that one the real eigenvalues is positive while the other is negative. Therefore, $\bar{\alpha}_1 > 0$ and $\bar{\alpha}_2 < 0$ because $\bar{\alpha}_1 > \bar{\alpha}_2$ from (33).

In particular, as observed before, it is crucial to ensure along the transition path a proper proportion of physical capital and environmental quality, which are fundamental ingredients in attracting tourism and, therefore, to guarantee the economic activity.

Knowing the eigenvalues $\bar{\alpha}_i$, we can identify a closed-form expression for the optimal trajectory of our economy and the corresponding speed of convergence, which represents the rate at which the economy (in level terms) approaches its steady-state:

Proposition 6. *For $\epsilon = \delta$, the optimal trajectory of the economy is given by*

$$\tilde{e}(t) = [\tilde{e}(0) - \tilde{e}^*] \exp\{\bar{\alpha}_2 t\} + \tilde{e}^*, \tag{34}$$

$$\tilde{c}(t) = \frac{v_{22}}{v_{12}}[\tilde{e}(0) - \tilde{e}^*] \exp\{\bar{\alpha}_2 t\} + \tilde{c}^*, \tag{35}$$

where (v_{12}, v_{22}) are the coordinates of the eigenvector corresponding to $\bar{\alpha}_2$, verifying that $v_{22}/v_{12} = -(1-\varphi)(\epsilon+\rho)/\bar{\alpha}_2\theta > 0$. Moreover, the speed of convergence of the economy is $\bar{\beta} \equiv -\bar{\alpha}_2$. So the time that the economy needs to reduce by half the difference with respect to the steady-state is $\bar{t} \equiv -\log(1/2)/\bar{\beta}$.

Proof. See Appendix E. □

The expressions (34) and (35) confirm the results in Proposition 5. The optimal trajectory of the economy exists and is unique. Moreover, since the eigenvalues are real numbers, the optimal solution is not oscillatory. Hence in absence of fluctuations due to, for instance, energy prices, international tourism demand, *etc.*, or without including further non-linearities in the evolution of the environmental conditions, the economy converges to its long-run equilibrium but does not exhibit cycles. As is clear in the proof of Proposition 6, these closed-form solutions also allows us to identify the formula for the speed of convergence. This is given by the expression (33) for the eigenvalue $\bar{\alpha}_2$. Let us then complete the analysis introduced in Section 4 about ecotourism, studying this time the effect of promoting this type of tourism on the rapidity with which the economy gets to its long-term equilibrium.

As pointed out before, ecotourism typically involves activities with low environmental impact. This effect is captured in our model by a reduction of the parameter ϑ. We have shown in Section 4 that promoting ecotourism allows the economy to sustain a greater level of physical capital, environmental quality, income, and tourism, together with higher consumption and long-run welfare. As is clear from Proposition 6 and equation (33), ϑ does not affect the speed of convergence. This is a direct consequence of the local approach of our dynamic analysis. One can easily verify in this regard that, in a neighborhood of the steady-state, the effect of ϑ is compensated by the response of e^*

and c^*.[15] Nevertheless, consistent with arguments made by the United Nations World Tourism Organization (UNWTO, 2002), ecotourism includes an additional dimension: "ecotourists" also give greater importance to the environmental conditions as an input in the provision of tourism services. As is clear from (6), this feature is represented in our model by a higher α, which is a parameter that affects the speed of convergence through φ in (33). So let us study the effect this second dimension of ecotourism on the long-run levels of the economy, as well as on the corresponding speed of convergence.

Considering the characterization of the steady-state in Proposition 3, it is possible to show that ecotourism can increase the long-term level of environmental quality because of its second dimension. More specifically, $\partial e^*/\partial \alpha > 0$ for a big enough α (see Appendix F for a detailed proof). Therefore, due to the greater role played by the environmental conditions in the provision of this type of tourism (a larger α), promoting ecotourism can reinforce the effect of its reduced environmental impact (a lower ϑ). Hence the resulting long-run environmental quality will be even larger. But this is only possible if the economy focuses on the provision of tourism services with large enough environmental content ($\alpha > \bar{\alpha}$ in Appendix F). Under this scenario we can also show that the effect on k^* is also reinforced, together with the reaction of the long-run level of GDP and tourism services (*i.e.*, $\partial k^*/\partial \alpha$ and $\partial y^*/\partial \alpha > 0$). Regarding the long-term consumption c^*, if we additionally require that the negative impact of tourism on environmental quality is low enough, the effect of ϑ on c^* will be reinforced as well. Thus c^* would be even greater, leading to higher welfare in the long-term.

From a long-term perspective, we have shown above that tourism that is sufficiently environmentally friendly (*i.e.*, $\alpha > \bar{\alpha}$ and $\vartheta < \bar{\vartheta}$), as is typically the case of ecotourism, allows the economy to achieve greater welfare. Let us consider now the transitional dynamic implications of ecotourism, focusing on the effect on the speed of convergence of the economy. Since the speed of convergence is given by $\bar{\beta} = -\bar{\alpha}_2$, one can verify that $\partial \bar{\beta}/\partial \alpha < 0$ by taking into account (33) and that $\varphi = \alpha + \gamma$. We can thus conclude that promoting this type of tourism reduces the speed of convergence of the economy. Due to the greater importance that ecotourists give to the environmental conditions (represented by a larger α in our model), the policy maker should be particularly attentive regarding the expansion of tourism and the subsequent environmental degradation. Thus the balanced development of physical capital and environmental conditions would require a slower development. We summarize these results in the following proposition:

[15] Our linearization around the steady-state implies that $B\frac{\sigma-\vartheta}{\alpha+\gamma}\exp\{-(1-\varphi)\tilde{e}^*\} - \frac{\alpha}{\alpha+\gamma}\sigma\exp\{\tilde{c}^* - \tilde{e}^*\} = \epsilon + n$ and $B(\sigma-\vartheta)\exp\{-(1-\varphi)\tilde{e}^*\} = \epsilon + \rho$. So, for fixed ϵ, n and ρ, the effect of ϑ should be exactly compensated by the variation of e^* and c^*.

Proposition 7. *For $\epsilon = \delta$, if the economy focuses on sufficiently environmental-friendly tourism (i.e., $\alpha > \bar{\alpha}$ and $\vartheta < \bar{\vartheta}$) the equilibrium levels will be higher, resulting in greater long-term welfare. Nevertheless, the convergence to the steady-state will be slower.*

Proof. See Appendix F. □

This outcome reveals a social cost of ecotourism. Promoting this type of tourism does not imply any additional monetary cost in our simple model. However, environmental-friendly tourism is not free of charge in terms of welfare. Let us consider a developing economy, where consumption per capita is lower than its long-run level, *i.e.*, $c(0) < c^*$ in our model. Ecotourism allows this economy to achieve a higher long-term welfare. But due to the slower development of the economy, this policy would affect the intergenerational equity, inducing a welfare sacrifice of current generations with respect to future ones. As we will discuss in the Concluding remarks, this result is also relevant when the policy maker explicitly chooses this type of tourism. The optimal choices in such a problem will depend on the relative importance that the society gives to the welfare of current and future generations.

We finally study the case where $\epsilon \neq \delta$, meaning that physical capital and environmental quality have different depreciation rates. This case might be associated with situations such as, for instance, tourism being the main source of environmental deterioration (*i.e.*, $\epsilon \to 0$). In contrast to the simplified case, the inclusion of this additional dimension reduces the analytical tractability of the problem, but will allow us to identify richer stability properties of the steady-state. Appendix G provides detailed proofs of the results considered for this case. The main difficulty with this case is that we cannot use the simplified dynamical system in Section 5, considering instead the general system (27)-(28). By log-linearizing this system around the steady-state we can characterize the determinant and trace of the corresponding Jacobian matrix, and thereby the stability properties of the long-run equilibrium. In this regard, we establish a proposition that completes the stability result previously introduced in Proposition 5:

Proposition 8. *For $\delta > \epsilon$, the steady-state is saddle-path stable iff $\gamma < \bar{\gamma}$. For $\delta < \epsilon$, the steady-state is saddle-path stable iff $\gamma > \bar{\gamma}$ and $\alpha > \bar{\alpha}$. The steady-state is unstable otherwise. Moreover, when the steady-state is saddle-path stable, the economy does not exhibit complex dynamics.*

Proof. See Appendix G. □

This proposition shows that the steady-state cannot be stable, so local indeterminacy is not possible. There is instead a unique optimal trajectory (*i.e.*, saddle-path stability), ensuring long-term economic activity. The policy maker should guarantee in this regard the proper evolution of the economic variables. This would include the provision of tourism services, together with the correct proportion of physical capital and environmental quality that this economic activity would require. A similar result was already identified for the simplified case $\epsilon = \delta$, where the steady-state is always saddle-path stable. The new proposition states that this conclusion also holds for the situation where physical capital and environmental quality have different depreciation rates. But the saddle-path property of the steady-state turns out to be richer than before. If the physical capital depreciates more than the "natural" deterioration of environmental quality ($\epsilon < \delta$), the economy can have saddle-path stability. However, this is only possible if the importance of physical capital in the provision of tourism services is low ($\gamma < \bar{\gamma}$). One should note that this case includes the possibility of considering that the environment deteriorates only due to the negative effect of tourism, that is to say, $\delta > \epsilon = 0$ in our model.[16] Regarding the situation where the depreciation rate of the environmental quality is greater than the one corresponding to physical capital ($\epsilon > \delta$), the steady-state can be saddle-path stable as well. But this time this is only possible if the weight of physical capital is big enough ($\gamma > \bar{\gamma}$). Notice that, for this case, we also require that the weight of the environmental quality is high ($\alpha > \bar{\alpha}$) in order to ensure that the threshold value for the weight of physical capital is lower than one, and so $\gamma > \bar{\gamma}$ can be possible for $\gamma < 1$. We should finally observe that, as in the simplified case, the convergence to the steady-state does not exhibits cycles either.[17]

6.2 Imbalance effect

We have seen in Proposition 1 that the policy maker should ensure a proper proportion of inputs for tourism, verifying $g(k(t), e(t)) = 0$ in every moment of time. This outcome is in line with the idea that the optimal behaviour of the economy requires a careful management of the tourism activities, incorporating the provision of this type of services and the evolution of the environmental conditions. This optimal condition implies that $k(t) = h(e(t))$ for all $t \geq 0$, being $h(e(t))$ an increasing function of $e(t)$. The optimal proportion of inputs can be explicitly stated in the simplified case, where the ratio $k(t)/e(t)$ equals a fixed constant $\gamma/\alpha\sigma$.

However, since the initial endowment of physical capital and environmental quality are intrinsic characteristics of the economy, nothing prevents us from having $k(0) \neq h(e(0))$. In this situation an imbalance effect arises if physical capital investment and abatement are assumed not to be negative, *i.e.*, $i(t) \geq 0$ and $m(t) \geq 0$ for all $t \geq 0$. This is

[16] All the results of the paper are valid for $\epsilon = 0$, keeping unchanged the conditions about the other parameters of the model.

[17] As we show in Appendix G, if the eigenvalues of the corresponding Jacobian matrix are complex the steady-state is unstable.

typically the case of considering irreversible investments in physical capital and/or in environmental quality. As we will state in the next proposition, under the presence of this imbalance effect the economy will reestablish the proportion between $k(t)$ and $e(t)$ during a finite number of periods T. Once the relationship $k(t) = h(e(t))$ is recovered the economy will behave as detailed before, starting instead at T:

Proposition 9. *If* $k(0) < h(e(0))$, $i(t) > 0$ *for* $t \geq 0$, *whereas* $m(t) = 0$ *for* $0 \leq t \leq T < \infty$ *and* $m(t) > 0$ *for* $t > T$. *If* $k(0) > h(e(0))$, $m(t) > 0$ *for* $t \geq 0$, *whereas* $i(t) = 0$ *for* $0 \leq t \leq T < \infty$ *and* $i(t) > 0$ *for* $t > T$.

Proof. See Appendix H. □

Let us focus on a small developing tourism economy, where the environmental quality is an important feature of attracting tourism. This is typically the case of many beach destinations such as, for instance, the Caribbean. These types of economies are frequently endowed with high environmental quality, which contrasts with the lack of infrastructures and tourism facilities. In our set-up these economies are identified as unbalanced situations, where the initial endowment of physical capital is relatively small with respect to the "environmental capital". Since $h(e(t))$ is an increasing function, we are in the case of $k(0) < h(e(0))$ in Proposition 9. According to this proposition, the economy will optimally sacrifice some of its initial environmental quality during the initial stages of development, concentrating on the accumulation of physical capital (that is to say, $i(t) > 0$ for $t \geq 0$, whereas $m(t) = 0$ for $0 < t \leq T$). So the economy temporally focuses on the creation of basic infrastructures, providing fundamental inputs to supply tourism services. However, since tourists are also attracted by the environmental quality, the economy should invest as well in environmental maintenance after this transitional phase in order to ensure the sustainability of the economic activity. Specifically, once the balance between environmental quality and physical capital is recovered (*i.e.*, $k(t) = h(e(t))$), the optimal behaviour of the economy from then on follows what was described in the previous section, investing in the maintentance of the environmental conditions too (*i.e.*, $i(t) > 0$ and $m(t) > 0$ for $t > T$). Numerous papers found evidence of this transitional phase (among others, McElroy and Albuquerque, 1998; Silva *et al.*, 2008; Santana-Jiménez and Hernández, 2011; and Silva and Ferreira, 2013). The main feature of this readjusting period is that the economy initially sacrifices part of its environmental quality, focusing on the provision of primary tourist infrastructures such as airports, roads, cruise docks, hotels, *etc.* Nevertheless, they also point out that the lack of planning and inadequate understanding of the dynamic interaction between tourism and the environmental quality have frequently caused an important threat to the sustainability of tourism and economic activity in many of these regions. The analytical results of our paper are indeed in line with the idea of a careful planing in order to sustain tourism and economic activity. In the context of the model, this outcome is mainly illustrated by the saddle-path stability of the steady-state (so the optimal trajectory is unique) and the optimal proportion between the physical capital and the environmental conditions.

7 Concluding remarks

We studied the dynamic interaction between tourism and environmental quality. First, we empirically confirmed the reverse causality between tourism and environmental quality, commonly only assumed in the literature. To this end we used the example of the Caribbean since its coastal environment and beaches made this region one of the most appealing destinations for tourists. To demonstrate dual causality we employed Granger causality tests on tourism arrivals and coastal nightlight intensity, the latter as a measure of overcrowding and its effects on seashore and beach environmental degradation. With this dual causality at hand, we then introduced a theoretical model in order to investigate the dynamic implications of this relationship. We found that, by investing in abatement activities that are sufficiently efficient, tourism can guarantee positive levels of environmental quality, GDP, and welfare in the long-term. We demonstrated, in particular, that ecotourism allows the economy to raise these levels but at the cost of slower economic development. We identified as well the importance of maintaining an optimal proportion of physical capital and environmental quality along the evolution of the economy. Thus careful planning and management would be required to sustain economic activity and welfare by means of tourism. Moreover, we also detected the presence of an imbalance effect behind this proportion, so that, during initial stages of its development, an economy endowed with rich environmental conditions can optimally sacrifice part of the environmental quality, focusing instead on building basic infrastructures for tourism.

Several extensions can be made to our work. We have considered nightlight intensity as a proxy of environmental degradation. The availability of this data as well as its local nature allowed us to measure the evolution of coastal and beaches environmental quality in the Caribbean. It could be interesting to use alternative proxies such as bathing water quality or coastal biodiversity in order to provide estimates of the impact of specific types of tourism (*e.g.*, beach tourism, cruise tourism, or ecotourism). As of date, however, the main drawback of these alternative approaches is data availability, which is particularly problematic in many developing tourism-based economies. Regarding our theoretical model, as in Mariani *et al.* (2015), we did not include any natural regeneration of the environmental conditions. Since adding this possibility would make sustainability easier, we focused on an extreme case in order to underline the negative effect of tourism on the environmental conditions of the economy. Nevertheless, taking into account the natural regeneration would allow the model to frame a more general and richer interaction between maintenance activities and the negative impact of tourism. Finally, in the context of our model, we consider that ecotourism involves activities with low environmental impact, giving at the same time great importance to the environmental quality of the economy. As we showed here, due to slower pace of the economy, this type of tourism has a social welfare cost in terms of intergenerational equity. A possible direction for further research could be to explicitly include the choice of the type of tourism, endogenizing then the effect of parameter ϑ in our set-up. In particular, if the policy maker opts for a tourism with high environmental content, she should take into account the intergenerational consequences of a slower development with a higher welfare for the future generations.

Appendices

A Proposition 1 proof

The FOC for $c(t)$ and $m(t)$ give $\lambda(t) = u'(c(t))$ and $\lambda(t) = \sigma\mu(t)$. Taking this outcome into the FOC for $e(t)$ and $k(t)$, we obtain

$$-\frac{\dot{\mu}(t)}{\mu(t)} = (\sigma - \vartheta)f'_e - (\epsilon + \rho), \tag{A.1}$$

$$-\frac{\dot{\lambda}(t)}{\lambda(t)} = \frac{\sigma - \vartheta}{\sigma}f'_k - (\delta + \rho). \tag{A.2}$$

Since $\lambda(t) = \sigma\mu(t)$,

$$\frac{\dot{\lambda}(t)}{\lambda(t)} = \frac{\dot{\mu}(t)}{\mu(t)}. \tag{A.3}$$

Moreover, knowing that $\lambda(t) = u'(c(t))$,

$$\frac{\dot{\lambda}(t)}{\lambda(t)} = \frac{u''(c(t))c(t)}{u'(c(t))}\frac{\dot{c}(t)}{c(t)}. \tag{A.4}$$

Considering (A.1)-(A.4), we then obtain the conditions of the proposition. Notice that (18) and (19) are obtained from the standard transversality conditions

$$\lim_{t\to\infty} \mu(t)e(t)\exp\{-(\rho - n)t\} = 0, \tag{A.5}$$

$$\lim_{t\to\infty} \lambda(t)k(t)\exp\{-(\rho - n)t\} = 0, \tag{A.6}$$

provided that, from the previous results, $\mu(t) = \mu(0)\exp\left(-\int_0^t [(\sigma - \vartheta)f'_e - \epsilon - n]ds\right)$ and $\mu(0) = \frac{1}{\sigma}u'(c(0))$.

B Proposition 3 proof

At the steady-state $\dot{c}(t) = 0$. Then, since $\xi(c(t)) \neq 0$, equations (14) and (17) imply that

$$f_e'^* = \frac{\epsilon + \rho}{\sigma - \vartheta} \tag{A.7}$$

and

$$f_k'^* = \frac{\sigma}{\sigma - \vartheta}(\delta + \rho). \tag{A.8}$$

Since $f_e' > 0$ and $f_k' > 0$ for all $e(t)$ and $k(t)$, we will need that $\vartheta < \sigma$. Using the Cobb-Douglas production function in (A.7) and (A.8), we directly obtain the unique steady-state (20) and (21), where $e^* > 0$ and $k^* > 0$. Equations (22) and (23) result from (15) and (16) when $\dot{k}(t) = 0$ and $\dot{e}(t) = 0$. Notice that, since $e^* > 0$ and $k^* > 0$, equation (22) allows us to conclude that $m^* > 0$. Moreover, replacing m^* in (23) from (22), together with the condition (21), yields

$$c^* = \frac{1}{\sigma} e^* \left[\frac{\epsilon + \rho}{\alpha} - \frac{\gamma(\epsilon + \rho)(\delta + n)}{\alpha(\delta + \rho)} - (\epsilon + n) \right]. \tag{A.9}$$

It is easy to verify that the term between brackets is strictly positive. So $c^* > 0$ because $e^* > 0$.

C Proposition 4 proof

Let us consider the definition of $g(e(t), k(t))$ in Proposition 1. We do a first-order approximation of this function around the steady-state equilibrium (e^*, k^*):

$$g(e(t), k(t)) \approx g(e^*, k^*) + g_e'(e^*, k^*)[e(t) - e^*] + g_k'(e^*, k^*)[k(t) - k^*]. \tag{A.10}$$

From the characterization of the steady-state in Proposition 3, since $g(e^*, k^*) = 0$, the linearization yields:

$$g(e(t), k(t)) \approx \frac{1}{k^*}[\gamma(\epsilon + \rho) + (1 - \gamma)(\delta + \rho)]k(t) - \frac{1}{e^*}[(1 - \alpha)(\epsilon + \rho) + \alpha(\delta + \rho)]e(t) + \beta(\epsilon - \delta). \tag{A.11}$$

Taking $g(e(t), k(t)) = 0$ in (A.11), and $k^* = \frac{\epsilon+\rho}{\sigma(\delta+\rho)} \frac{\gamma}{\alpha} e^*$ from Proposition 3, we obtain the relationship (24) of the proposition.

D Phase diagram

Figure 1 depicts the phase diagram for the system (29)-(30).[18] From equation (29), we directly identify the locus where $\dot{c}(t) = 0$ (vertical line in Figure 1), which is given by

[18]Since for this case we do not need to linearize $g(e(t), k(t))$, the phase diagram analysis is valid for both local and global dynamics.

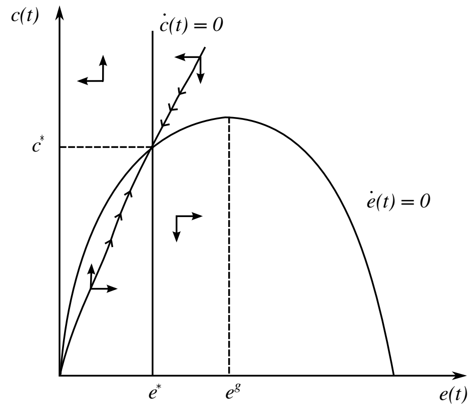

Figure 1: Phase diagram.

$e(t) = e^*$. By fixing $c(t) = \bar{c}$ in (29), one can conclude that $\partial \dot{c}(t)/\partial e(t) < 0$ and, therefore, the direction of motion. The locus where $\dot{e}(t) = 0$ is determined from the other differential equation (30):

$$c(t) = \frac{1}{\sigma}\frac{\alpha+\gamma}{\alpha}\left[B\frac{\sigma-\vartheta}{\alpha+\gamma}e(t)^{\alpha+\gamma} - (\delta+n)e(t)\right], \tag{A.12}$$

which is a concave function, where e^g in Figure 1 represents the level of environmental quality that maximizes the steady-state consumption per capital, *i.e.*, the golden rule environmental conditions. Since $B(\sigma-\vartheta)e^{*(\alpha+\gamma)-1} = (\epsilon+\rho)$ and $B(\sigma-\vartheta)e^{g(\alpha+\gamma)-1} = (\epsilon+n)$, one should observe that $e^* < e^g$ because we have assumed that in our economy $\rho > n$ (see Section 3). Finally, the direction of motion is determined by fixing $e(t) = \bar{e}$ in (30), and concluding afterwards that $\partial \dot{e}(t)/\partial c(t) < 0$. Drawing the two loci together in Figure 1, we clearly see that the economy optimally follows a unique stable manifold (saddle-path stability), monotonically converging to the steady-state identified in Proposition 3.[19]

E Proposition 6 proof

Let us rewrite the system (31) as $\dot{M}(t) = JM(t) + B$, where M and B are the corresponding matrices. We define as well the matrices

$$D \equiv \begin{bmatrix} \bar{\alpha}_1 & 0 \\ 0 & \bar{\alpha}_2 \end{bmatrix}, \quad V \equiv \begin{bmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \end{bmatrix}, \tag{A.13}$$

where (v_{11}, v_{21}) and (v_{12}, v_{22}) are, respectively, the eigenvectors of the eigenvalues $\bar{\alpha}_1$ and $\bar{\alpha}_2$. Since $\bar{\alpha}_1 \neq \bar{\alpha}_2$, the matrix J has two distinct eigenvalues and, therefore, it is diagonalizable. Under this situation, the eigenvectors are linearly independent, so

[19]Notice that transitional paths outside the stable manifold are not optimal because they would violate feasibility and TC. Regarding TC, let us observe that $(\sigma-\vartheta)f_e'(\bar{e}) < \epsilon + n$ for every constant $\bar{e} > e^g$ since $f_e'(e(t)) = Be(t)^{(\alpha+\gamma)-1}$.

$\det(V) \neq 0$ and

$$V^{-1} = \frac{1}{\det(V)} \begin{bmatrix} v_{22} & -v_{12} \\ -v_{21} & v_{11} \end{bmatrix}. \tag{A.14}$$

Our system (31) can be easily solved by means of the change of variable $Z(t) \equiv V^{-1}M(t)$. Since $V^{-1}JV = D$, $\dot{Z}(t) = DZ(t) + V^{-1}B$. The transformed system involves two independent linear differential equations because D is a diagonal matrix. Solving each equation, and undoing the change of variable as $M(t) = VZ(t)$, yields

$$\begin{bmatrix} \dot{\tilde{e}}(t) \\ \dot{\tilde{c}}(t) \end{bmatrix} = \begin{bmatrix} v_{11}\psi_1 \exp\{\bar{\alpha}_1\} + v_{12}\psi_2 \exp\{\bar{\alpha}_2\} + \tilde{e}^* \\ v_{21}\psi_1 \exp\{\bar{\alpha}_1\} + v_{22}\psi_2 \exp\{\bar{\alpha}_2\} + \tilde{c}^* \end{bmatrix}. \tag{A.15}$$

We know that $\bar{\alpha}_1 > 0$ and $\bar{\alpha}_2 < 0$. It is clear from (A.15) that $\psi_1 = 0$ in order to satisfy feasibility and TC. The other constant is determined since $e(0)$ is given: $\psi_2 = v_{12}^{-1}[\tilde{e}(0) - \tilde{e}^*]$. We then obtain (34) and (35). Computing the corresponding eigenvectors of $\bar{\alpha}_2$, it is easy to verify that $v_{22}/v_{12} = -(1-\varphi)(\epsilon+\rho)/\bar{\alpha}_2\theta > 0$. Finally, defining $\bar{\beta} \equiv -\bar{\alpha}_2$ and rearranging terms in (34), we can state that

$$\tilde{e}(t) = (1 - \exp\{-\bar{\beta}t\})\tilde{e}^* + \tilde{e}(0)\exp\{-\bar{\beta}t\}. \tag{A.16}$$

So $\bar{\beta}$ is the speed of convergence of the economy. Notice that, since $y(t) = Ae(t)^\alpha k(t)^\gamma$ and $k(t) = \frac{1}{\sigma}\frac{\gamma}{\alpha}e(t)$, we get from (A.16) a similar expression for the income per capita of the economy: $\tilde{y}(t) = (1 - \exp\{-\bar{\beta}t\})\tilde{y}^* + \tilde{y}(0)\exp\{-\bar{\beta}t\}$. As usual we obtain $\bar{t}$ by equating $\exp\{-\bar{\beta}\bar{t}\} = 1/2$.

F Proposition 7 proof

We study the effect of decreasing ϑ simultaneously with an increasing of α (*i.e.*, the adoption of environmental-friendly tourism in the context of our model) on the steady-state equilibrium identified in Proposition 3. For a steady-state variable $x^* = \{e^*, k^*, y^*, c^*\}$, $dx^* = (\partial x^*/\partial\vartheta)d\vartheta + (\partial x^*/\partial\alpha)d\alpha$. We know from before that $\partial x^*/\partial\vartheta < 0$. So $(\partial x^*/\partial\vartheta)d\vartheta > 0$ for a decreasing ϑ. We just need to verify that $\partial x^*/\partial\alpha > 0$ in order to ensure that increasing α reinforces the positive effect of decreasing ϑ on x^*. Considering the close-form expression for e^*, we can see that $\partial e^*/\partial\alpha > 0$ for $\alpha > \bar{\alpha}$, where

$$\bar{\alpha} \equiv \left[\frac{1}{A(\sigma - \vartheta)}\right]^{\frac{1}{1-\gamma}} \left[\frac{\sigma(\delta+n)}{\gamma}\right]^{\frac{\gamma}{1-\gamma}} (\epsilon+\rho). \tag{A.17}$$

Under this condition we confirm that $\partial k^*/\partial\alpha > 0$ as well. Moreover, since $y^* = f(e^*, k^*)$, we can confirm that $\partial y^*/\partial\alpha > 0$ because $f_i' > 0$. Let us study the sign of $\partial c^*/\partial\alpha$. We define the elasticity of e^* with respect to α as $E \equiv \frac{\partial e^*}{\partial\alpha}\frac{\alpha}{e^*}$. Taking equation (21) and rewriting the $\partial c^*/\partial\alpha$ in terms of E, we can state that $\partial c^*/\partial\alpha > 0$ iff the elasticity $E > \bar{E}$, for $\bar{E} \equiv \frac{\bar{A}}{\bar{A}-(\epsilon+n)}$ where $\bar{A}$ is the following combination of parameters of our model:

$$\bar{A} \equiv \frac{\epsilon+\rho}{\alpha}\left(1-\gamma\frac{\delta+n}{\delta+\rho}\right). \tag{A.18}$$

Notice that, since we already know that $c^* > 0$, one can verify that $\bar{E} > 0$. Moreover $\bar{A} > 0$ because we have assumed that $\rho > n$ (see equation 11). Since $\bar{E}$ does not depend on ϑ, and $\frac{\partial E}{\partial \vartheta} = -\frac{\alpha}{(1-\alpha-\gamma)(\sigma-\vartheta)} < 0$, the condition $E > \bar{E}$ holds if ϑ is low enough. Consequently, $\partial c^*/\partial\alpha > 0$ for $\vartheta < \bar{\vartheta}$. The threshold $\bar{\vartheta}$ is just the value of ϑ such that $E = \bar{E}$, that is to say,

$$\frac{1-\gamma}{1-\alpha-\gamma} + \frac{\alpha}{(1-\alpha-\gamma)^2}\log\left[A\left(\frac{\gamma}{\delta+\rho}\right)^{\gamma}\left(\frac{\alpha}{\epsilon+\rho}\right)^{1-\gamma}\sigma^{-\gamma}(\sigma-\bar{\vartheta})\right] = \bar{E}. \tag{A.19}$$

Rearranging terms in this expression, we can conclude that $\bar{\vartheta} = \sigma - \exp\{\Upsilon\}$ where Υ is defined as

$$\Upsilon \equiv \frac{(1-\alpha-\gamma)^2}{\alpha}\left[\bar{E} - \frac{1-\gamma}{1-\alpha-\gamma}\right] - \log\left[A\left(\frac{\gamma}{\delta+\rho}\right)^{\gamma}\left(\frac{\alpha}{\epsilon+\rho}\right)^{1-\gamma}\sigma^{-\gamma}\right]. \tag{A.20}$$

We have to finally ensure that $\bar{\vartheta} > 0$ since ϑ is a positive parameter in our model. In this respect the inequality $\sigma > \exp\{\Upsilon\}$ must hold. Taking the previous expression for Υ, and rearranging terms in the inequality, we can identify a threshold value for σ

$$\bar{\sigma} = \exp\left\{\frac{1}{1-\gamma}\left\{\frac{(1-\alpha-\gamma)^2}{\alpha}\left[\bar{E} - \frac{1-\gamma}{1-\alpha-\gamma}\right] - \log\left[A\left(\frac{\gamma}{\delta+\rho}\right)^{\gamma}\left(\frac{\alpha}{\epsilon+\rho}\right)^{1-\gamma}\right]\right\}\right\} \tag{A.21}$$

so that $\sigma > \bar{\sigma}$. In Proposition 3, we have already observed that the efficiency of maintenance must be large enough ($\sigma > \vartheta$). We then just need to set $\sigma > \max\{\vartheta, \bar{\sigma}\}$ in order to ensure that $\bar{\vartheta} > 0$. Notice that, once $\partial c^*/\partial\alpha > 0$ is ensured, the effect of ϑ on c^* will be reinforced. Consequently, the increase of the long-run welfare of the economy will be greater as well.

G Case $\epsilon \neq \delta$ proofs

The log-linearization of the system (27)-(28) around the steady-state results in the following linear differential system:

$$\begin{bmatrix} \dot{\tilde{e}}(t) \\ \dot{\tilde{c}}(t) \end{bmatrix} = J \times \begin{bmatrix} \tilde{e}(t) \\ \tilde{c}(t) \end{bmatrix} + \begin{bmatrix} -\Omega_1\tilde{e} - \Omega_2\tilde{c} \\ -\upsilon_1\tilde{e} \end{bmatrix}, \tag{A.22}$$

where J is the Jacobian matrix of the system, evaluated at the steady-state:

$$J \equiv \begin{bmatrix} \Omega_1 & \Omega_2 \\ \upsilon_1 & 0 \end{bmatrix}, \tag{A.23}$$

for

$$\Omega_1 \equiv \left[1 + \frac{\gamma(\epsilon+\rho)}{\alpha(\delta+\rho)}\Phi_1\right]^{-1} \left\{(\alpha+\gamma\Phi_1)\frac{\epsilon+\rho}{\alpha} - \left[\frac{\gamma(\delta+n)(\epsilon+\rho)}{\alpha(\delta+\rho)}(1-\Phi_2) + (\epsilon+n)\right]\right\}, \tag{A.24}$$

$$\Omega_2 \equiv \left[1 + \frac{\gamma(\epsilon+\rho)}{\alpha(\delta+\rho)}\Phi_1\right]^{-1} \left\{(\epsilon+n) - \frac{\epsilon+\rho}{\alpha}\left[\frac{(\delta+\rho)-\gamma(\delta+n)}{\delta+\rho}\right]\right\}, \tag{A.25}$$

$$\upsilon_1 \equiv \frac{1}{\theta}(\epsilon+\rho)[\gamma\Phi_1 - (1-\alpha)]. \tag{A.26}$$

For this system the eigenvalues of matrix J are

$$\bar{\alpha}_i = \frac{1}{2}\left(\Omega_1 \pm \sqrt{\Omega_1^2 + 4\upsilon_1\Omega_2}\right), \tag{A.27}$$

for $i = \{1, 2\}$. Let us study the sign of Ω_1, Ω_2 and υ_1 in order to identify the stability properties of the steady-state. Taking the definition of Ω_1, we can show by contradiction that Ω_1 is a strictly positive constant. Regarding the sign of Ω_2, we additionally define

$$\bar{\gamma} \equiv \frac{\delta+\rho}{\delta+n} - \alpha\frac{\delta+\rho}{\delta+n}\frac{\epsilon+n}{\epsilon+\rho}, \tag{A.28}$$

$$\bar{\alpha} \equiv \frac{\rho-n}{\delta+\rho}\frac{\epsilon+n}{\epsilon+\rho}, \tag{A.29}$$

which are strictly positive constants. Moreover, since $\rho > n$, it is easy to see that $\bar{\alpha} < 1$. So we can conclude that:

- If $\gamma = \bar{\gamma}$ then $\Omega_2 = 0$.
- If $\gamma < \bar{\gamma}$ then $\Omega_2 < 0$.
- If $\gamma > \bar{\gamma}$ and $\alpha > \bar{\alpha}$ then $\Omega_2 > 0$.

Since in our model $\gamma \in (0, 1)$, the condition for α is required in order to ensure that $\bar{\gamma} < 1$. Indeed, if $\alpha \leq \bar{\alpha}$ then $\bar{\gamma} \geq 1$ ($= 1$ if $\alpha = \bar{\alpha}$). So γ would be smaller than $\bar{\gamma}$, which is the case corresponding to $\Omega_2 < 0$. Considering the definition of υ_1, since $\Phi_1 + \Phi_2 = 1$, we can show that:

- If $\delta > \epsilon$ then $\upsilon_1 < 0$.
- If $\delta < \epsilon$ then $\upsilon_1 > 0$.

We put together the previous conclusions about the signs of Ω_1, Ω_2 and υ_1. Let us first consider the case $\delta > \epsilon$. For this situation we proved before that $\upsilon_1 < 0$. If we additionally include the condition $\gamma < \bar{\gamma}$ we know that $\Omega_2 < 0$. So the eigenvalues are real and, moreover, $\det(J) < 0$. Since $\det(J) = \bar{\alpha}_1\bar{\alpha}_2$ the steady-state will be saddle-path stable. If we instead assume that $\gamma > \bar{\gamma}$, together with $\alpha > \bar{\alpha}$ in order to ensure that $\bar{\gamma} < 1$, then $\Omega_2 > 0$ and $\det(J) > 0$. Moreover, the eigenvalues can be complex. For the case of real eigenvalues the steady-state is not saddle-path stable because $(\bar{\alpha}_1, \bar{\alpha}_2) > 0$

or $(\bar{\alpha}_1, \bar{\alpha}_2) < 0$, which respectively correspond to the situations of instability or stability. Since $\mathrm{tr}(J) = \bar{\alpha}_1 + \bar{\alpha}_2$, the steady-state is unstable because $\mathrm{tr}(J) = \Omega_1 > 0$. For the case of complex eigenvalues, the steady-state is unstable too because the real part of $\bar{\alpha}_i$ is $\Omega_1 > 0$.

Following a similar reasoning we obtain the set of results for $\delta < \epsilon$. For this case $\upsilon_1 > 0$. If $\gamma > \bar{\gamma}$ and $\alpha > \bar{\alpha}$ then $\Omega_2 > 0$. Moreover, the eigenvalues are real and the steady-state is saddle-path stable. However, if $\gamma < \bar{\gamma}$ then $\Omega_2 < 0$. If the eigenvalues are real, the steady-state is unstable because $\det(J) < 0$ and $\mathrm{tr}(J) > 0$. If the eigenvalues are complex, the steady-state is unstable because $\Omega_1 > 0$. Notice that, for all previous cases about δ and ϵ, if $\gamma = \bar{\gamma}$ and $\alpha > \bar{\alpha}$ then $\Omega_2 = 0$. So $\bar{\alpha}_1 = \Omega_1$ and $\bar{\alpha}_2$. Consequently, the steady-state is unstable because $\Omega_1 > 0$.

H Proposition 9 proof

Without lost of generality, we will consider the case $k(0) < h(e(0))$. The proof can be easily adapted for the situation where $k(0) > h(e(0))$. Let us rewrite the social optimum problem as

$$\max_{\{i,m\}} \int_0^\infty u(f(e(t), k(t)) - i(t) - m(t)) \exp(-(\rho - n)t) dt$$

subject to

$$\begin{cases} \dot{k}(t) = i(t) - (\delta + n)k(t), \\ \dot{e}(t) = \sigma m(t) - (\epsilon + n)e(t) - \vartheta f(e(t), k(t)). \end{cases}$$

The idea of the proof is to conjecture that the economy will set $i(t) > 0$ for all $t \geq 0$, however $m(t) = 0$ for $0 \leq t \leq T < \infty$, and $m(t) > 0$ for $t > T$. We should then prove that the conjecture is a solution of the social optimum problem.

Taking into account the positivity constraints for $i(t)$ and $m(t)$, the Hamiltonian of the problem is

$$H(i, m, k, e, \mu, \lambda, \chi_k, \chi_e) = u(f(e(t), k(t)) - i(t) - m(t)) + \lambda(t)[i(t) - (\delta + n)k(t)]$$
$$+\mu(t)[\sigma m(t) - \vartheta f(e(t), k(t)) - (\epsilon + n)e(t)] + \chi_k(t)i(t) + \chi_e m(t), \tag{A.30}$$

where $\chi_e(t)$ and $\chi_k(t)$ are the auxiliary multipliers associated to the positivity constraints. The FOC of the problem are $\partial H/\partial k(t) = (\rho - n)\lambda(t) - \dot{\lambda}(t)$, $\partial H/\partial e(t) = (\rho - n)\mu(t) - \dot{\mu}(t)$, $\partial H/\partial i(t) = 0$, $\partial H/\partial m(t) = 0$, $\chi_k(t)i(t) = 0$, $\chi_e(t)m(t) = 0$, $\chi_k(t) \geq 0$, and $\chi_e(t) \geq 0$. Therefore, considering the Hamiltonian (A.30),

$$u'(c(t))f'_k - (\delta + n)\lambda(t) - \vartheta f'_k \mu(t) = (\rho - n)\lambda(t) - \dot{\lambda}(t),$$

$$u'(c(t))f'_e - (\epsilon + n)\mu(t) - \vartheta f'_e \mu(t) = (\rho - n)\mu(t) - \dot{\mu}(t),$$

$$-u'(c(t)) + \lambda(t) + \chi_k(t) = 0,$$

$$-u'(c(t)) + \sigma\mu(t) + \chi_e(t) = 0,$$

where $c(t) = f(e(t), k(t)) - i(t) - m(t)$. Since in our conjecture $i(t) > 0$ then $\chi_k(t) = 0$. So $\lambda(t) = u'(c(t))$ from the FOC. We know moreover that $\lambda(t) = \sigma\mu(t)$ (see Appendix A). Therefore, we also conclude from that

$$\frac{\sigma - \varphi}{\sigma} f'_k - \delta - \rho = -\frac{\dot{\lambda}(t)}{\lambda(t)}. \tag{A.31}$$

Differentiating $\lambda(t) = u'(c(t))$ with respect to time, and taking (A.31), we obtain the corresponding Euler condition of our problem:

$$\frac{\dot{c}(t)}{c(t)} = \frac{1}{\xi(c(t))} \left[\frac{\sigma - \varphi}{\sigma} f'_k(e(t), k(t)) - \delta - \rho \right]. \tag{A.32}$$

Hence, for $t \in [0, T]$ the dynamic behaviour of our economy is characterized by the equation (A.32), together with laws of motion:

$$\dot{k}(t) = \frac{\sigma - \varphi}{\sigma} f(e(t), k(t)) - c(t) - (\delta + n)k(t), \tag{A.33}$$

$$\dot{e}(t) = -\varphi f(e(t), k(t)) - (\epsilon + n)e(t). \tag{A.34}$$

Notice that, for the Cobb-Douglas technology (6), equation (A.34) is a Bernoulli's differential equation, which has a unique solution with a well-known close-form (for instance, Sydsæter *et al.*, 2005, p.70). So we can express $e(t)$ as a unique function of $k(t)$, *i.e.*, $e(t) = s(k(t))$. Moreover, since $f(e(t), k(t)) \geq 0$ the environmental quality always decreases for $t \in [0, T]$. This allows us to conclude that $T < \infty$ because this would otherwise contradict the fact that the economy optimally ends up in a positive steady-state $e(t) = e^* > 0$.

Let us assume that, for $t \geq T$, $m(t) > 0$ such that $k(t) = h(e(t))$. We can therefore describe the behaviour of $e(t)$ as:

$$e(t) = \eta(k(t)) \equiv \max\{h^{-1}(k(t)), s(k(t))\}. \tag{A.35}$$

Consequently, the system that we have to solve comprises equation (A.32) together with the law of motion of physical capital (A.33), where $e(t) = \eta(k(t))$. This is a dynamical system of two equations and two unknowns, with the initial condition $k(0)$ and the usual transversality condition (19). As observed in Acemoglu (2009, p.386) and Peters and Simsek (2009, p.167), even if this system is not autonomous it is very similar to the neoclassical growth model. So there exists a unique level of $c(0)$ such that the transversality condition will be satisfied, *i.e.*, we have saddle path stability. Therefore, our conjecture satisfies the FOC and the transversality and initial conditions.

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