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## Article

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Annals of Tourism Research Empirical Insights

## Provided in Cooperation with:

Elsevier

*Suggested Citation:* Rodrigo, M.; Ajala, Imène; Irhanida, A. K. (2023) : Qualitative analysis of a tourism area life cycle model for interacting tourism destinations, Annals of Tourism Research Empirical Insights, ISSN 2666-9579, Elsevier, Amsterdam, Vol. 4, Iss. 1, pp. 1-12, <https://doi.org/10.1016/j.annale.2023.100093>

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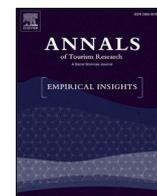
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# Qualitative analysis of a tourism area life cycle model for interacting tourism destinations

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## ARTICLE INFO

### Keywords:

Tourism area life cycle  
Competition  
Mutualism  
Predator–prey  
Interacting tourism destinations

## ABSTRACT

An extension of the tourism area life cycle (TALC) model is proposed by considering two interacting tourism destinations. Three types of interaction dynamics are investigated: competition, mutualism (or cooperation) and predator–prey. Using dynamical systems theory, a qualitative analysis of the proposed model is performed and all possible tourist equilibria are identified. These three interaction dynamics are then discussed from the perspective of nation-branding and competitive identity in the context of the race for soft power, and further illustrated empirically with examples from Malaysia and the Middle East.

## 1. Introduction

Since Butler's original article (Butler, 1980) on tourism destination development, the tourism area life cycle (TALC) model has been extensively discussed and is generally accepted as a conceptual heuristic for understanding the evolution of tourism destinations (Pearce, 1989; Butler, 2006a, 2006b). The model assumes a sigmoidal life cycle in the growth of a tourism destination with identifiable stages, namely exploration, involvement, development, consolidation and stagnation. The poststagnation stage is usually either a decline or rejuvenation. Several papers have analysed and elaborated the assumptions, generality and practicality of the TALC model (Haywood, 1986; Lundtorp & Wanhill, 2001; Hovinen, 2002; Cole, 2009).

The model remains a seminal contribution thanks to its 'powerful analytical framework' (Jones, 2012, 182), its flexibility (Knowles & Curtis, 1999), its usefulness for planning (Polyzos, Tsiotas, & Kantlis, 2013, 165), its value in addressing cycles of growth in the tourism environment (Petrevska & Collins-Kreiner, 2017) or 'its integration of an economic and territorial interpretation of tourism' (Garay & Canoves, 2011, 653). On the other hand, the TALC model has also been criticised for its limitations such as the lack of precision, its excessive reliance on one parameter (i.e. the number of visitors) (Polyzos et al., 2013), its little explanatory power (Andergassen, Candela, & Figini, 2013), its homogeneous approach to tourism destination neglecting the differentiation between destinations (Knowles & Curtis, 1999; Jones, 2012; Chapman &

Light, 2016), its lack of empirical grounding (McKercher & Wong, 2021; Koens, Smit, & Melissen, 2021) or its application to a national dimension while it was initially formulated for a single destination (Jones, 2012).

In this paper, we propose an extension of the TALC model by considering two tourism destinations whose respective tourists interact with each other, much like the way in which two population species interact. Hence, in this sense, we can speak of 'interacting tourism destinations' as in the title of this paper. We study three types of dynamics that are often considered for interacting population species, namely competition, mutualism (or cooperation) and predator–prey. Using dynamical systems theory, we perform a qualitative analysis of the proposed model and thus identify all possible tourist equilibria or steady states.

The outline of the article is as follows. In Section 2, we provide a brief literature review with regard to the TALC model, with a particular emphasis on how research has addressed the limits of the model. We particularly draw attention to the novelty of considering the model in the framework of interacting destinations. In Section 3, we formulate the mathematical model for interacting tourism destinations as a pair of coupled differential equations, find all possible steady states and provide a summary of their classification and stability. The detailed calculations are given in the Appendix. We present the results of numerical simulations in Section 4 and discuss the implications of the mathematical results from the viewpoints of tourism, international relations and economics in Section 5. Brief concluding remarks are given in Section 6.

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## 2. Literature review

From the mid 2000s until the present, there has been an increase in the number of results that provided empirical tests of the TALC model and attempted to formalise its underlying processes. For instance, [Zhong, Deng, and Xiang \(2008\)](#) applied the model to national parks and other protected areas, specifically to China's Zhangjiajie National Forest Park. They discussed the external and internal factors that affect the park's tourism development, as well as the environmental, social and economic changes in the area. [Nejad and Tularam \(2010\)](#) used the TALC framework for tourist arrivals in Queensland, Australia. They concluded that the stagnation stage was yet to be reached, thus providing many growth opportunities for the Australian tourism industry. [Omar, Othman, Mohammed, and Bahauddin \(2015\)](#) described the life cycles of coastal resorts in Tioman Island, Malaysia, by using historical and fieldwork data dating back to the start of the 1890s. They concluded that the resorts in the island have passed through the first four stages as described in the TALC model and were in the consolidation stage. [Kristjánsdóttir \(2015\)](#) applied the model to estimate the maximum tourism level. To capture the nonmonotonic relationship of the cycle, a fifth-degree polynomial was put forward that accounts for government, banks, roads, skilled labour and internet application. Results indicated that the sigmoidal shape of Butler's tourist area cycle of evolution can be captured with a polynomial function for a range of OECD countries including Norway and Iceland. [Kraja and Beshiri \(2019\)](#) fitted logistic and Gompertz-type models to data of tourist arrivals to Albania. Using data from the period 2001–18, they made forecasts of carrying capacities for foreign tourist arrivals by sea and land.

Another strand in the literature has tried to address the limits of the model by looking at variables, actors or new forces that were previously neglected. As a result of the COVID-19 pandemic, tourism managers now have to carefully assess the impact of epidemics on their businesses and develop new risk management methods to cope with the crisis. One avenue of development that has arisen is rural tourism. [Bucur \(2021\)](#) defined a so-called entropy of rural tourism that is useful to measure uncertainty, and derived a differential equation satisfied by the entropy. More recently, [Jena and Behera \(2022\)](#) proposed a mathematical model for a tourism supply chain under two scenarios, namely ecotourism effort with and without cost sharing. They utilised game-theoretic models to compare equilibrium outcomes for the two scenarios. In another perspective, [Holmes and Ali-Knight \(2017\)](#) adapted the TALC model to the study of events and festivals, which are central assets for the promotion of a tourism destination. Events and festivals can thus act as 'catalysts' for reviving destinations in a decline phase ([Holmes & Ali-Knight, 2017](#)).

Others have reformulated specific stages of the model such as the poststagnation stage ([Knowles & Curtis, 1999](#)), factored in environmental sustainability ([Cerina, 2007](#)) or focused on the role of the government ([Petrevska & Collins-Kreiner, 2017](#)). Another example regarding the inclusion of environmental sustainability can be found in [Casagrandi and Rinaldi \(2002\)](#). They developed a theoretical approach to tourism sustainability by proposing a minimal model that incorporates many features such as number of tourists, quality of the natural environment and capital for tourist activities. Their model consists of three coupled nonlinear ordinary differential equations. They showed that tourism sustainability can be achieved provided the agents are cautious in reinvesting their benefits and are willing to protect the environment, and that sustainability is often at risk since accidental 'shocks' can easily trigger a switch from a profitable/compatible behaviour to an unprofitable/incompatible one. With regard to the role of the government, [Kubickova and Li \(2017\)](#) showed in their study about tourism in Costa Rica, Guatemala and Honduras how the engagement of the government to address the competitiveness of a tourism destination can change in accordance with the TALC stages. The government's involvement may be higher at an early stage as it can provide incentives to encourage investors. But once the development has taken off, it can

take a back seat to allow for more efficiency in a free-market, liberal perspective. In other words, by providing a range of incentives, public policies play a major role in the first two stages of the TALC model, exploration and involvement ([Kubickova & Li, 2017](#)). Governments can thus develop more efficient strategies depending on an adequate identification of the TALC stage, especially to prevent decline ([Kubickova & Li, 2017](#); [Albaladejo & Martínez-García, 2019](#)). In the analysis of Spanish tourism, this translates into a recommendation to increase the attractiveness of inland destinations so as to have a more equal distribution of the tourist population in the coasts to ultimately ensure more sustainable tourism ([Albaladejo & Martínez-García, 2019](#)).

Most results in the literature on the evaluation of potential tourism development are descriptive or qualitative, which are not as effective when comparing the tourism potential of heritage sites in a region. [Yan, Gao, and Zhang \(2017\)](#) developed an operable quantitative approach to measuring the potential of heritage sites and demonstrated its effectiveness by applying it to two Chinese heritage sites. [Lundtorp and Wanhill \(2001\)](#) found that the logistic model describes the first five stages of the TALC model. However, since the logistic model assumes a fixed tourism market ceiling, it fails to explain the poststagnation stage when rejuvenation or decline may occur. Thus [Albaladejo and Martínez-García \(2017\)](#) investigated the poststagnation stage for mature tourism areas by proposing a multilogistic model, where investment or innovation in the tourism sector boosts the addition of new logistic curves which superpose the old ones. A number of new theoretical models have also emerged ([Andergassen et al., 2013](#)). Some have called for combining the TALC model with other theories, such as regulation theories, to reinforce the longitudinal perspective of the model and ultimately seize more efficiently the periods of restructuring of the industry following periods of structural crisis associated to legal, political or institutional changes ([Garay & Canoves, 2011](#)). [Andergassen et al. \(2013, 87\)](#) suggested looking at aspects of tourism that are usually overlooked, namely 'the issue of coordination between local firms and the degree of sophistication of the tourism product' in order to increase the explanatory power of the original TALC model. Others have explored the use of methods from design science and design thinking ([Koens et al., 2021](#)).

Even conceptually, the ontological assumptions on which the TALC model relies with regard to its approach of what constitutes a tourism destination have been deconstructed. The concept of tourism destination has indeed been revisited, with several scholars emphasising its multidimensionality and suggesting, at the epistemological level, approaches more rooted in micro- and macro-economic theories. [Candela and Figini \(2010\)](#) emphasised the complexity of the tourism product associating several goods and services, while [Chapman and Light \(2016\)](#) approached it as a mosaic. [Andergassen et al. \(2013, 94\)](#) more precisely redefined the tourism destination into 'a bundle composed of a set of elementary items' and, based on the significance of the territorial dimension, a '(meta) economic agent taking important decisions from the supply side at an intermediate level to the micro- (firms and tourists) and macro-levels (the entire country's economy)'. This complexity means that several agents are involved in the provision of this bundle which, in turn, implies that planning and policy of a particular destination will depend on these various agents' coordination and cooperation ([Andergassen, Candela, & Figini, 2017](#)).

Indeed, one of the main limitations of the TALC model inspiring the research in this article is that it originally did not explore the relation between the stages of development and processes like competition or cooperation between destinations. The role of a travel agent becomes more complex in a setting where tourism destinations compete over visitors. This is precisely what [Wachsman \(2006\)](#) demonstrated in his study where inter-destination competition tends to cancel out the advantages of intra-destination competition when a monopolistic multi-player is able to intervene in these destinations. [Wachsman \(2006, 541\)](#) invites researchers to go further by exploring the role of 'capacity constraints, non-linear demands, stochastic demand and multiple firms

in each destination’.

McKercher and Wong (2021) empirically tested the proposition of complexity theory stipulating that destinations have multiple life cycles with results pointing to the coevolution of destinations, highlighting how the life cycle of a destination is not isolated but rather embedded in a pattern. Andergassen et al. (2017) analysed strategies of cooperation and temporality. They considered the choice for private agents to play cooperative or non-cooperative strategies, and from the point of view of temporality, the simultaneous or sequential dimension of the actors’ moves that ultimately determine the best choice for the policymaker. They concluded with the ‘absolute importance of coordination between stakeholders’ with regard to not only the quality and quantity of goods and services, but also to the pricing (Andergassen et al., 2017, 61). Andergassen et al. (2013, 95) also suggested to extend their model into a framework factoring in inter-destination competition while taking into account the existence of multi-destination players (e.g. hotel chains) precisely acting in all these destinations. Butler and Weidenfeld (2012) also addressed this gap by providing a model focusing on the relation between the proximity of the tourist destinations and the extent of local or regional cooperation or competition throughout the stages of the TALC. Cooperation, translating into partnerships, networks, consortiums or simple collaborations, can improve competitiveness as they ‘generate external economies of scale, reduce risks and overcome the growth of complexity, fragmentation and turbulence as tourism develops in an area’ (Butler & Weidenfeld, 2012, 16). Clusters arising from this cooperation and development into agglomeration economies, as per Butler and Weidenfeld’s terminology, can benefit from a range of pooled resources including labour, infrastructures or information services. Butler and Weidenfeld (2012, 23) invite researchers to further analyse the patterns of collaboration between different stakeholders throughout the different TALC stages and determine which forces drive the optimal conditions favouring such collaboration. The present article explores this direction further.

Romano (2016) used a nonautonomous (i.e. the coefficients in the model depend explicitly on time), but integrable, Lotka–Volterra model to investigate tourist patterns in the three Italian regions of Campania, Puglia and Liguria. One of the conclusions in Romano (2016) was that there is a variety of interaction dynamics among tourism destinations, e.g. competition, mutualism, commensalism and predator–prey. However, it should be pointed out that although the integrable Lotka–Volterra model considered in Romano (2016) is analytically tractable, the system of differential equations was chosen to have a very special structure that is arguably not realistic from a modelling viewpoint. The approach we follow here is similar in spirit to that of Romano (2016) but we do not assume a special structure in the underlying equations.

### 3. Model formulation and qualitative analysis

We model the interaction between two tourism destinations by describing the interaction between the tourists that visit each tourism destination. Let  $T_j(t)$  (where  $j = 1, 2$ ) denote the number of tourists visiting destination  $j$  at time  $t \geq 0$ . In the absence of any interaction, we follow a TALC framework by assuming that the tourist dynamics are described by logistic-type models

$$\frac{dT_1}{dt} = r_1 T_1 \left( 1 - \frac{T_1}{K_1} \right), \quad \frac{dT_2}{dt} = r_2 T_2 \left( 1 - \frac{T_2}{K_2} \right),$$

where  $r_j > 0$  is the intrinsic growth rate and  $T_{j,\infty} = K_j > 0$  is the tourist equilibrium or steady state for destination  $j$ .

**Remark 3.1.** If the initial tourist population is such that  $0 < T_j(0) < K_j$  (respectively,  $T_j(0) > K_j$ ), then  $T_j(t)$  is monotonic increasing (respectively, monotonic decreasing) in  $t$  and  $T_j(t) \rightarrow T_{j,\infty} = K_j$  as  $t \rightarrow \infty$ . Hence the tourist population for destination  $j$  reaches its maximum level, also known as the tourist carrying capacity, when  $0 < T_j(0) < K_j$ . However,

even though  $K_j$  is not the maximum level reached when  $T_j(0) > K_j$ , it is still standard in population studies to refer to the steady state  $T_{j,\infty} = K_j$  as the tourist carrying capacity (Brauer & Castillo-Chávez, 2012).

When the tourist population numbers are small,  $dT_1/dt \simeq r_1 T_1$  and  $dT_2/dt \simeq r_2 T_2$ . Thus tourist populations will grow exponentially for small times, but growth will eventually slow down due to limitations in resources as the tourist carrying capacities are approached. As is well known, these behaviours induce sigmoidal growth curves for the tourist populations as assumed in the TALC model.

Next, let us introduce the effects of interaction. Assuming the Law of Mass Action, a standard modelling approach in population ecology (Brauer & Castillo-Chávez, 2012), we propose the following model:

$$\begin{aligned} \frac{dT_1}{dt} &= r_1 T_1 \left( 1 - \frac{T_1}{K_1} \right) - \frac{r_1 \alpha_{12}}{K_1} T_1 T_2 = r_1 T_1 \left( 1 - \frac{T_1}{K_1} - \alpha_{12} \frac{T_2}{K_1} \right), \\ \frac{dT_2}{dt} &= r_2 T_2 \left( 1 - \frac{T_2}{K_2} \right) - \frac{r_2 \alpha_{21}}{K_2} T_1 T_2 = r_2 T_2 \left( 1 - \frac{T_2}{K_2} - \alpha_{21} \frac{T_1}{K_2} \right). \end{aligned} \tag{3.1}$$

Here,  $\alpha_{ij}$  (where  $i, j = 1, 2$  and  $i \neq j$ ) is a nonzero parameter that reflects the influence destination  $j$  has on destination  $i$ . Depending on the signs of  $\alpha_{12}$  and  $\alpha_{21}$ , we can consider different types of interaction dynamics, borrowing the terminology for interacting population species (Brauer & Castillo-Chávez, 2012):

- (C) competition dynamics, i.e.  $\alpha_{12} > 0$  and  $\alpha_{21} > 0$
- (M) mutualism (or cooperation) dynamics, i.e.  $\alpha_{12} < 0$  and  $\alpha_{21} < 0$
- (P) predator–prey dynamics, i.e.  $\alpha_{12} < 0$  and  $\alpha_{21} > 0$ .

Note that with the way we expressed the interaction terms in (3.1), the parameters  $\alpha_{12}$  and  $\alpha_{21}$  are dimensionless. An interpretation of  $\alpha_{ij}$  is as follows. Each of the equations in (3.1) can be expressed as

$$\frac{1}{T_i} \frac{dT_i}{dt} = r_i \left( 1 - \frac{T_i}{K_i} - \alpha_{ij} \frac{T_j}{K_i} \right). \tag{3.2}$$

The left-hand side of (3.2) represents the per capita growth rate of the tourist population for destination  $i$ , and is influenced by destination  $j$  through  $\alpha_{ij}$ . Suppose for the moment that  $\alpha_{ij}$  is small in magnitude (i.e.  $|\alpha_{ij}| \ll 1$ ). Then we observe that when  $T_i < K_i$ , the per capita growth rate is positive (increasing tourist population), but when  $T_i > K_i$ , the per capita growth rate is negative (decreasing tourist population). If  $|\alpha_{ij}|$  is increased, and depending on whether  $\alpha_{ij}$  is positive or negative according to the three types of dynamics above, a corresponding change in the per capita growth rates can be observed. Hence  $\alpha_{12}$  and  $\alpha_{21}$  directly influence the tourist population per capita growth rates.

**Remark 3.2.** In the classical Lotka–Volterra predator–prey model (Brauer & Castillo-Chávez, 2012), the per capita growth rate of one species in the absence of the other is assumed a constant. However, in (3.2) under the dynamics (P), it is a negatively sloped linear function of the population size, which leads to a logistic model for each species in the absence of the other. This assumption rules out periodic solutions, unlike in the classical Lotka–Volterra predator–prey model.

#### 3.1. Determination and interpretation of the steady states

The system of differential equations in (3.1) is nonlinear and cannot be solved analytically in general. Hence we perform a qualitative analysis instead. There are four equilibria or steady states obtained by setting the right-hand sides of (3.1) to zero. The first three are  $P_1 = (0, 0)$ ,  $P_2 = (K_1, 0)$  and  $P_3 = (0, K_2)$ , which always exist under (C), (M) and (P). The fourth steady state  $P_4 = (T_{1,\infty}, T_{2,\infty})$  is calculated by solving the linear algebraic system

$$T_{1,\infty} + \alpha_{12} T_{2,\infty} = K_1, \quad \alpha_{21} T_{1,\infty} + T_{2,\infty} = K_2, \tag{3.3}$$

whose solution

$$P_4 = (T_{1,\infty}, T_{2,\infty}) = \left( \frac{K_1 - \alpha_{12}K_2}{1 - \alpha_{12}\alpha_{21}}, \frac{K_2 - \alpha_{21}K_1}{1 - \alpha_{12}\alpha_{21}} \right) \tag{3.4}$$

exists provided that  $T_{1,\infty} > 0$  and  $T_{2,\infty} > 0$ . We will refer to  $T_{1,\infty}$  and  $T_{2,\infty}$  in (3.4) as the coexistence tourist population sizes.

The equilibrium  $P_1$  describes the state where there are no tourists in both destinations. The equilibrium  $P_2$  (respectively,  $P_3$ ) is when the tourist steady state for destination 1 (respectively, destination 2) in the absence of interaction is reached, with the corresponding disappearance of the other tourist population. Finally, the equilibrium  $P_4$  represents a coexistence state.

### 3.2. Conditions for the existence of the coexistence steady state

For (C), if  $K_1 - \alpha_{12}K_2$  and  $K_2 - \alpha_{21}K_1$  are both positive (respectively, both negative), then  $\alpha_{12}\alpha_{21} < 1$  (respectively,  $\alpha_{12}\alpha_{21} > 1$ ). Therefore  $T_{1,\infty} > 0$  and  $T_{2,\infty} > 0$ . For (M), we deduce that  $K_1 - \alpha_{12}K_2 > 0$  and  $K_2 - \alpha_{21}K_1 > 0$  since  $\alpha_{12} < 0$  and  $\alpha_{21} < 0$ . Then  $T_{1,\infty} > 0$  and  $T_{2,\infty} > 0$  if  $\alpha_{12}\alpha_{21} < 1$ . For (P), since  $\alpha_{12} < 0$  and  $\alpha_{21} > 0$ , we have  $K_1 - \alpha_{12}K_2 > 0$  and  $\alpha_{12}\alpha_{21} < 0 < 1$ , so that  $T_{1,\infty} > 0$ . Thus  $T_{2,\infty} > 0$  if  $K_2 > \alpha_{21}K_1$ . The conditions for the existence of  $P_4 = (T_{1,\infty}, T_{2,\infty})$  under each of the interaction dynamics are summarised in Table 1.

### 3.3. Implications on the tourist equilibria in the presence of interaction

Suppose that the coexistence equilibrium  $P_4 = (T_{1,\infty}, T_{2,\infty})$  exists, and consider the different types of interaction dynamics (C), (M) or (P). For (C), either  $K_1 - \alpha_{12}K_2$  and  $K_2 - \alpha_{21}K_1$  are both positive or both negative. If  $K_1 - \alpha_{12}K_2 > 0$  and  $K_2 - \alpha_{21}K_1 > 0$ , then multiplying  $\alpha_{12} < K_1/K_2$  and  $\alpha_{21} < K_2/K_1$  yields  $\alpha_{12}\alpha_{21} < 1$ . It follows that

$$T_{1,\infty} = \frac{K_1 - \alpha_{12}K_2}{1 - \alpha_{12}\alpha_{21}} < K_1, \quad T_{2,\infty} = \frac{K_2 - \alpha_{21}K_1}{1 - \alpha_{12}\alpha_{21}} < K_2.$$

The same results hold if  $K_1 - \alpha_{12}K_2 < 0$  and  $K_2 - \alpha_{21}K_1 < 0$ . Hence, as a result of competition, the coexistence tourist population sizes for both destinations are reduced.

For (M), we see that  $K_1 > \alpha_{12}K_2$  and  $K_2 > \alpha_{21}K_1$  since  $\alpha_{12}$  and  $\alpha_{21}$  are both negative. Multiplying  $\alpha_{12} < K_1/K_2$  and  $\alpha_{21} < K_2/K_1$  gives  $\alpha_{12}\alpha_{21} < 1$ . It follows that

$$T_{1,\infty} = \frac{K_1 - \alpha_{12}K_2}{1 - \alpha_{12}\alpha_{21}} > K_1, \quad T_{2,\infty} = \frac{K_2 - \alpha_{21}K_1}{1 - \alpha_{12}\alpha_{21}} > K_2.$$

Hence, because of mutualism (or cooperation), the coexistence tourist population sizes for both destinations are increased.

Finally, for (P), the inequalities  $K_1 - \alpha_{12}K_2 > 0, K_2 - \alpha_{21}K_1 > 0$  (see Table 1) and  $\alpha_{12}\alpha_{21} < 0 < 1$  imply that

$$T_{1,\infty} = \frac{K_1 - \alpha_{12}K_2}{1 - \alpha_{12}\alpha_{21}} > K_1, \quad T_{2,\infty} = \frac{K_2 - \alpha_{21}K_1}{1 - \alpha_{12}\alpha_{21}} < K_2.$$

Thus predator–prey dynamics increase the coexistence tourist population size for one and decrease the coexistence tourist population size for the other.

**Table 1**

Conditions for the existence of the coexistence equilibrium  $P_4 = (T_{1,\infty}, T_{2,\infty})$ .

Dynamics	$P_4 = (T_{1,\infty}, T_{2,\infty})$ exists if
(C)	$(K_1 - \alpha_{12}K_2)(K_2 - \alpha_{21}K_1) > 0$
(M)	$\alpha_{12}\alpha_{21} < 1$
(P)	$K_2 > \alpha_{21}K_1$

### 3.4. Classification and stability of the steady states

An important consideration is, under each of the interaction dynamics (C), (M) or (P), which steady states can be reached. Hence we need to investigate the stability of the steady states. The classification and stability of the equilibria can be summarised in the following subsections; see the Appendix for the detailed calculations.

Refer to Table 2, for (C1), we conclude that destination 1 outcompetes destination 2 and trajectories in the phase plane in general tend to  $P_2$ . A similar situation occurs for (C2), where the roles are reversed and  $P_2$  is replaced by  $P_3$ . Adopting the terminology of population ecology, we refer to scenarios (C1) or (C2) as competitive exclusion or Gause’s Principle. The idea is that two tourism destinations competing for the same limited resource (e.g. tourists) cannot coexist because when one has an advantage over the other, the one with the advantage will dominate in the long term, leading to ‘extinction’ of the ‘weaker’ tourism destination. Coexistence occurs in (C3) and trajectories in the phase plane in general tend to  $P_4$ . For (C4), the eventual steady state, either  $P_2$  or  $P_3$ , will depend on the initial tourist populations. In population ecology, founder-controlled communities will occur if species are approximately equivalent in their ability to colonise an opening left by a disturbance, and the winner is the species that happens to reach and establish itself in the disturbed location first. Hence, in a tourism context, we refer to (C4) as founder control and the species analogues are tourism destinations that are equally ‘attractive’. The eventual state depends on the initial tourist populations.

Refer to Table 3, we observe that there are no stable steady states in (M1). For (M2), trajectories in the phase plane in general tend to the coexistence equilibrium  $P_4$ .

Refer to Table 4, for (P1) (respectively, (P2)), trajectories in the phase plane in general tend to  $P_2$  (respectively,  $P_4$ ).

## 4. Numerical simulations

In the following numerical simulations, we fix  $r_1 = 0.01, r_2 = 0.02, K_1 = 10$  and  $K_2 = 20$ . The values for  $\alpha_{12}$  and  $\alpha_{21}$  are chosen depending on the interaction dynamics and scenario being considered. The equilibria in the phase plane are denoted by cyan dots. For each figure, the graph on the left represents the behaviour of the solution trajectories in the  $T_1T_2$ -plane, while the graph on the right represents the time profiles of  $T_1$  and  $T_2$  for given initial conditions.

### 4.1. Competition dynamics (C)

To satisfy scenario (C1), let  $\alpha_{12} = 0.2$  and  $\alpha_{21} = 2.2$ . We see that trajectories in Fig. 1a in general tend to  $P_2 = (K_1, 0)$ , which is asymptotically stable. Thus  $T_1$  reaches  $K_1$  (the tourist carrying capacity for  $T_1$  in the absence of  $T_2$ ), while  $T_2$  experiences decline. In Fig. 1b, we see that  $T_1$  goes through the stages of exploration, involvement, development, consolidation and stagnation, while  $T_2$  reaches its peak (less than  $K_2$ ) much sooner and then declines.

The reverse situation occurs for scenario (C2), where we choose  $\alpha_{12} = 0.8$  and  $\alpha_{21} = 1.6$ . Now, trajectories in Fig. 2a in general tend to the asymptotically stable equilibrium  $P_3 = (0, K_2)$ . Thus  $T_2$  reaches  $K_2$  (the tourist carrying capacity for  $T_2$  in the absence of  $T_1$ ), while  $T_1$  declines. In Fig. 2b, we observe that  $T_2$  goes through the stages of exploration, involvement, development, consolidation and stagnation, while  $T_1$  reaches its peak (less than  $K_1$ ) earlier and then experiences decline.

Let  $\alpha_{12} = 0.3$  and  $\alpha_{21} = 1.5$  in scenario (C3). Using (3.4), we obtain the coexistence steady state  $P_4 \simeq (7.27, 9.09)$  and is asymptotically stable, while the other equilibria are unstable. Trajectories in Fig. 3a in general tend to  $P_4$ . We see in Fig. 3b that  $T_2$  goes through the stages of exploration, involvement, development, consolidation and stagnation. Then it tends to a coexistence tourist population size approximately 9.09 and less than  $K_2$ . On the other hand,  $T_1$  reaches its peak and completes the stagnation stage, followed by a period of decline but tends to a

**Table 2**

Four scenarios under (C).

Type	Conditions	$P_1 = (0, 0)$	$P_2 = (K_1, 0)$	$P_3 = (0, K_2)$	$P_4 = (T_{1,\infty}, T_{2,\infty})$
(C1)	$K_1 > \alpha_{12}K_2, K_2 < \alpha_{21}K_1$	unstable node	asymptotically stable node	unstable saddle point	does not exist
(C2)	$K_1 < \alpha_{12}K_2, K_2 > \alpha_{21}K_1$	unstable node	unstable saddle point	asymptotically stable node	does not exist
(C3)	$K_1 > \alpha_{12}K_2, K_2 > \alpha_{21}K_1$	unstable node	unstable saddle point	unstable saddle point	asymptotically stable node
(C4)	$K_1 < \alpha_{12}K_2, K_2 < \alpha_{21}K_1$	unstable node	asymptotically stable node	asymptotically stable node	unstable saddle point

**Table 3**

Two scenarios under (M).

Type	Conditions	$P_1 = (0, 0)$	$P_2 = (K_1, 0)$	$P_3 = (0, K_2)$	$P_4 = (T_{1,\infty}, T_{2,\infty})$
(M1)	$\alpha_{12}\alpha_{21} \geq 1$	unstable node	unstable saddle point	unstable saddle point	does not exist
(M2)	$\alpha_{12}\alpha_{21} < 1$	unstable node	unstable saddle point	unstable saddle point	asymptotically stable node

coexistence tourist population size approximately 7.27 and less than  $K_1$ .

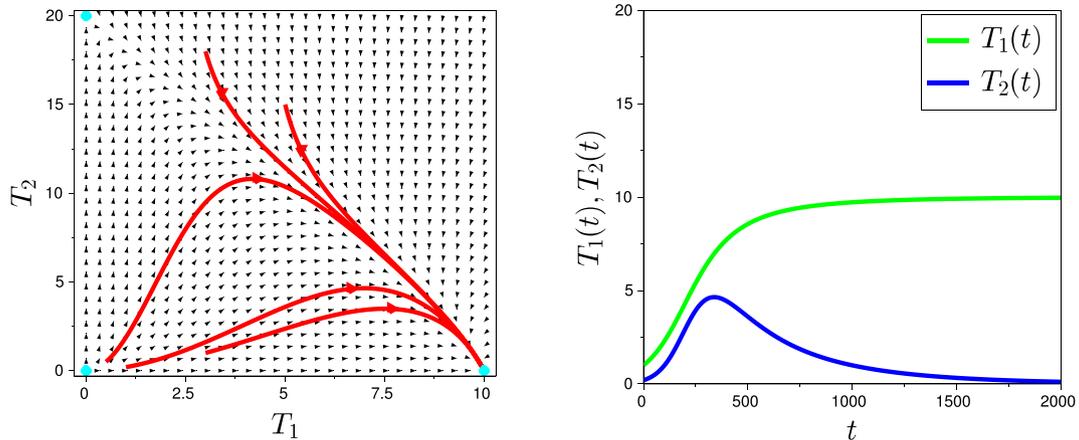
Suppose that  $\alpha_{12} = 0.8$  and  $\alpha_{21} = 3$  in scenario (C4). This time (3.4) gives the coexistence steady state  $P_4 \simeq (4.29, 7.14)$ , which is unstable, as is  $P_1 = (0, 0)$ . However,  $P_2 = (K_1, 0)$  and  $P_3 = (0, K_2)$  are asymptotically

stable. The eventual steady state will depend on how close the initial tourist populations are to  $P_2$  or  $P_3$ . In dynamical systems terminology,  $P_2$  and  $P_3$  have their respective basins of attraction. If the initial populations lie in the basin of attraction of  $P_2$  (respectively,  $P_3$ ), then the

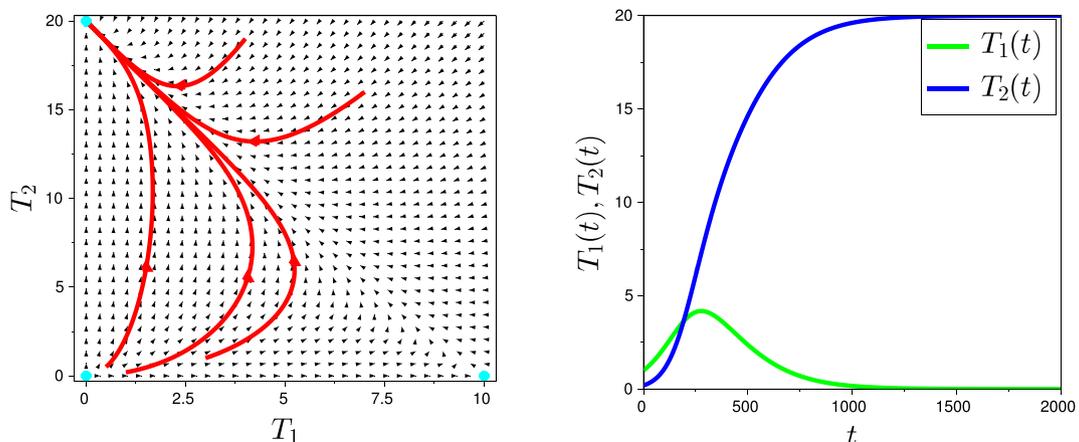
**Table 4**

Two scenarios under (P).

Type	Conditions	$P_1 = (0, 0)$	$P_2 = (K_1, 0)$	$P_3 = (0, K_2)$	$P_4 = (T_{1,\infty}, T_{2,\infty})$
(P1)	$K_2 < \alpha_{21}K_1$	unstable node	asymptotically stable node	unstable saddle point	does not exist
(P2)	$K_2 > \alpha_{21}K_1$	unstable node	unstable saddle point	unstable saddle point	asymptotically stable node



**Fig. 1.** Scenario (C1), where  $r_1 = 0.01, r_2 = 0.02, K_1 = 10, K_2 = 20, \alpha_{12} = 0.2$  and  $\alpha_{21} = 2.2$ .



**Fig. 2.** Scenario (C2), where  $r_1 = 0.01, r_2 = 0.02, K_1 = 10, K_2 = 20, \alpha_{12} = 0.8$  and  $\alpha_{21} = 1.6$ .

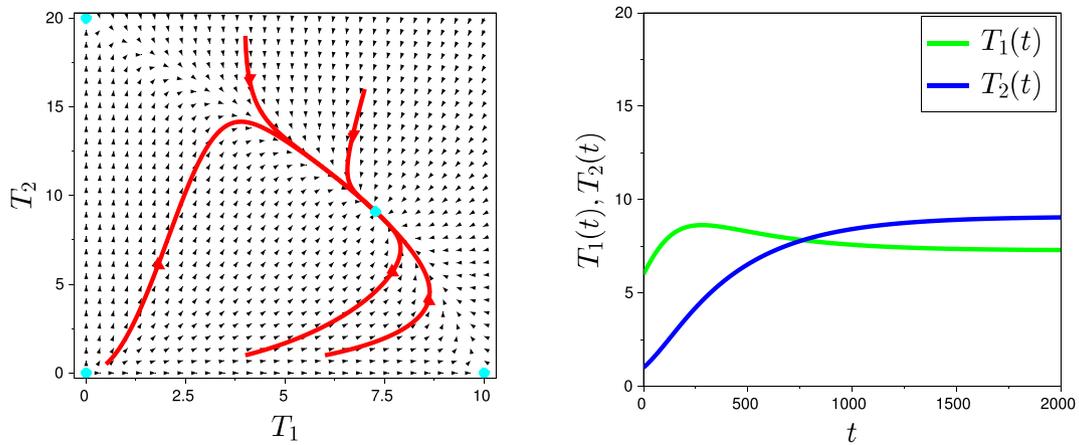


Fig. 3. Scenario (C3), where  $r_1 = 0.01, r_2 = 0.02, K_1 = 10, K_2 = 20, \alpha_{12} = 0.3$  and  $\alpha_{21} = 1.5$ .

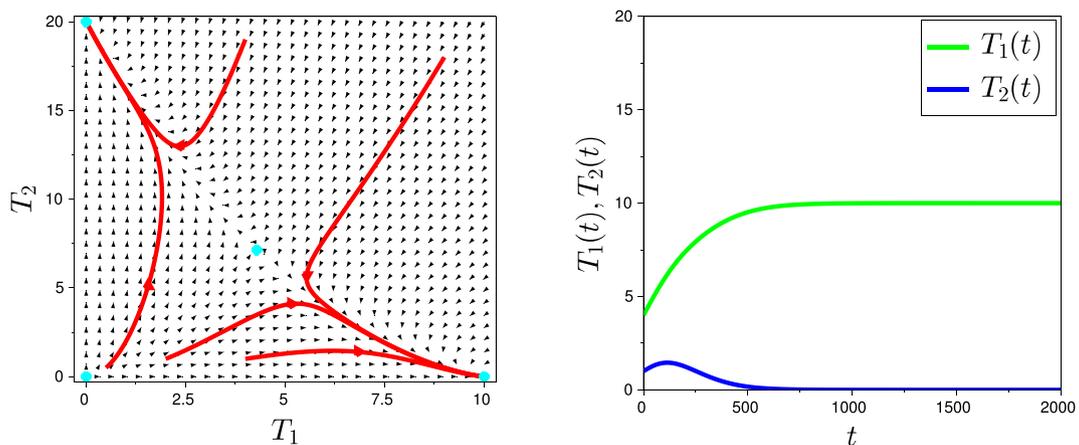


Fig. 4. Scenario (C4), where  $r_1 = 0.01, r_2 = 0.02, K_1 = 10, K_2 = 20, \alpha_{12} = 0.8$  and  $\alpha_{21} = 3$ .

solution trajectory tends to  $P_2$  (respectively,  $P_3$ ). In Fig. 4b, we deduce that the initial tourist populations lie in the basin of attraction of  $P_2$  since  $T_1$  tends to  $K_1$  while  $T_2$  tends to zero.

#### 4.2. Mutualism (or cooperation) dynamics (M)

To satisfy scenario (M1), let  $\alpha_{12} = -0.5$  and  $\alpha_{21} = -2.2$ . We note that trajectories in Fig. 5a in general become unbounded since  $P_1 = (0, 0), P_2 = (K_1, 0)$  and  $P_3 = (0, K_2)$  are unstable, while the coexistence

steady state  $P_4 = (T_{1,\infty}, T_{2,\infty})$  does not exist. In Fig. 5b, we see that  $T_1$  and  $T_2$  increase without bound with increasing time. As this is unrealistic, we do not expect this scenario to occur in practice.

Let  $\alpha_{12} = -0.5$  and  $\alpha_{21} = -0.3$  in scenario (M2). Using (3.4), we obtain the coexistence steady state  $P_4 \simeq (14.9, 24.5)$  and is asymptotically stable, while the other equilibria are unstable. Trajectories in Fig. 6a in general tend to  $P_4$ . We see in Fig. 6b that both  $T_1$  and  $T_2$  go through the stages of exploration, involvement, development, consolidation and stagnation. Then  $T_1$  (respectively,  $T_2$ ) tends to a coexistence

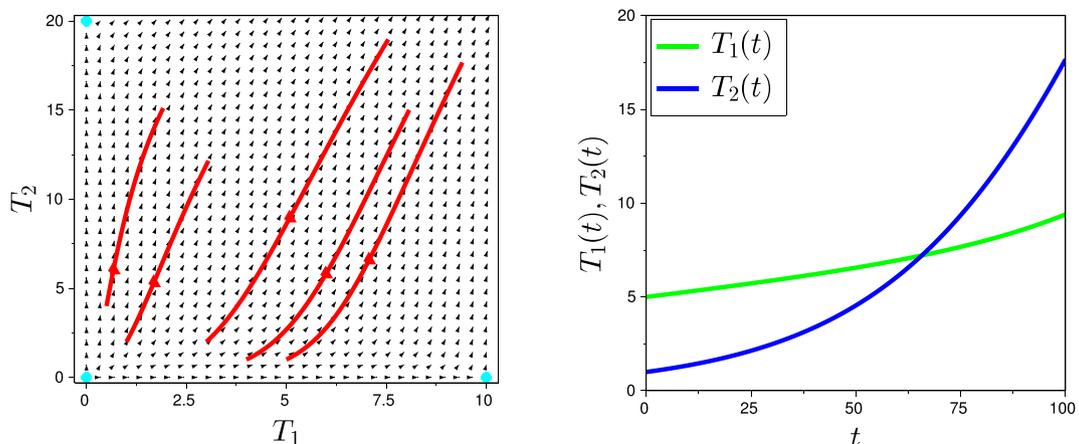


Fig. 5. Scenario (M1), where  $r_1 = 0.01, r_2 = 0.02, K_1 = 10, K_2 = 20, \alpha_{12} = -0.5$  and  $\alpha_{21} = -2.2$ .

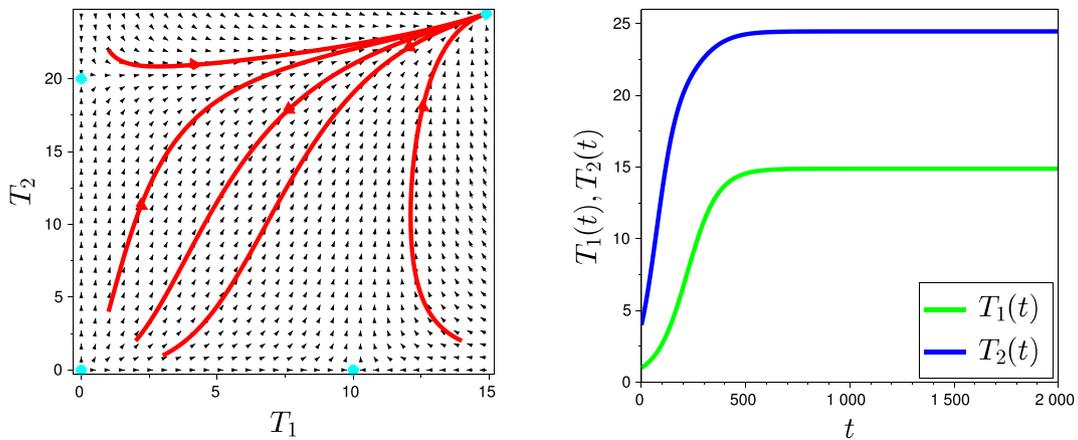


Fig. 6. Scenario (M2), where  $r_1 = 0.01, r_2 = 0.02, K_1 = 10, K_2 = 20, \alpha_{12} = -0.5$  and  $\alpha_{21} = -0.3$ .

tourist population size approximately 14.9 (respectively, 24.5) and greater than  $K_1$  (respectively,  $K_2$ ).

### 4.3. Predator-prey dynamics (P)

To satisfy scenario (P1), let  $\alpha_{12} = -0.2$  and  $\alpha_{21} = 2.2$ . Note that trajectories in Fig. 7a in general tend to  $P_2 = (K_1, 0)$ , which is asymptotically stable. Thus  $T_1$  reaches  $K_1$  (the tourist carrying capacity for  $T_1$  in the absence of  $T_2$ ), while  $T_2$  declines. In Fig. 7b, we observe that  $T_1$  goes through the stages of exploration, involvement, development, consolidation and stagnation, while  $T_2$  reaches its peak (less than  $K_2$ ) earlier and then declines.

Let  $\alpha_{12} = -0.2$  and  $\alpha_{21} = 1.5$  in scenario (P2). Using (3.4), we obtain the coexistence steady state  $P_4 \approx (10.8, 3.9)$  and is asymptotically stable, while the other equilibria are unstable. Trajectories in Fig. 8a in general tend to  $P_4$ . We see in Fig. 8b that  $T_1$  goes through the stages of exploration, involvement, development, consolidation and stagnation. Then it tends to a coexistence tourist population size approximately 10.8 and greater than  $K_1$ . On the other hand,  $T_2$  reaches its peak (less than  $K_2$ ) sooner but instead of declining to zero, it tends to a positive value approximately 3.9. Hence, even with predator-prey dynamics, it is possible to have a coexistence state.

## 5. Discussion

It was mentioned in the literature review that Lundtorp and Wanhill (2001) found that the logistic model describes the first five stages of the TALC model. However, since the logistic model assumes a fixed tourism market ceiling, it fails to explain the poststagnation stage, where

rejuvenation or decline may occur. As illustrated in the numerical simulations, some aspects of the poststagnation stage (e.g. decline) may be explained if we do not view a tourism destination as a single entity but rather as part of a system of interacting tourism destinations. Our model (3.1) can therefore be considered as an alternative to using a multi-logistic growth model for a single tourism destination (Albaladejo & Martínez-García, 2017).

Butler and Weidenfeld (2012, 23) hypothesised that when destinations approach the consolidation stage, businesses are more likely to direct their resources to competition with other intra-destination cluster businesses (local competition). This would be at the expense of marketing through membership in regional alliances (regional cooperation) for the purpose of competing with other destinations (regional competition). They concluded that regional competition would be expected to level off in the stagnation phase and even begin to decrease. This situation seems to be evident for the competition scenario (C3) in Fig. 3b. Butler and Weidenfeld (2012, 23) also noted that beyond the stagnation stage, decline or rejuvenation may ensue in the TALC, but cooperation between individual neighbouring businesses could remain at the same level as earlier since some businesses may try to increase tourist numbers by strengthening linkages and business cooperation in marketing with their neighbours. This apparent coexistence might be observed in the mutualism scenario (M2) in Fig. 6b. Although outside the scope of this article, but relevant to the above observations, an interesting idea is to investigate how competition dynamics can turn into mutualism dynamics. One way to model this is to replace the constants  $\alpha_{12}$  and  $\alpha_{21}$  by suitable time-dependent functions that change sign from positive to negative. Of course, the results of the qualitative analysis obtained here are not directly applicable since the modified system

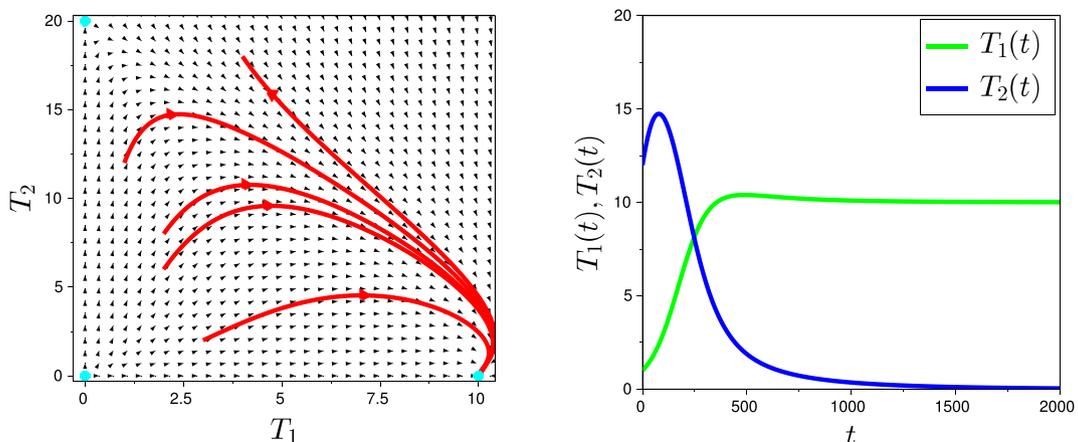


Fig. 7. Scenario (P1), where  $r_1 = 0.01, r_2 = 0.02, K_1 = 10, K_2 = 20, \alpha_{12} = -0.2$  and  $\alpha_{21} = 2.2$ .

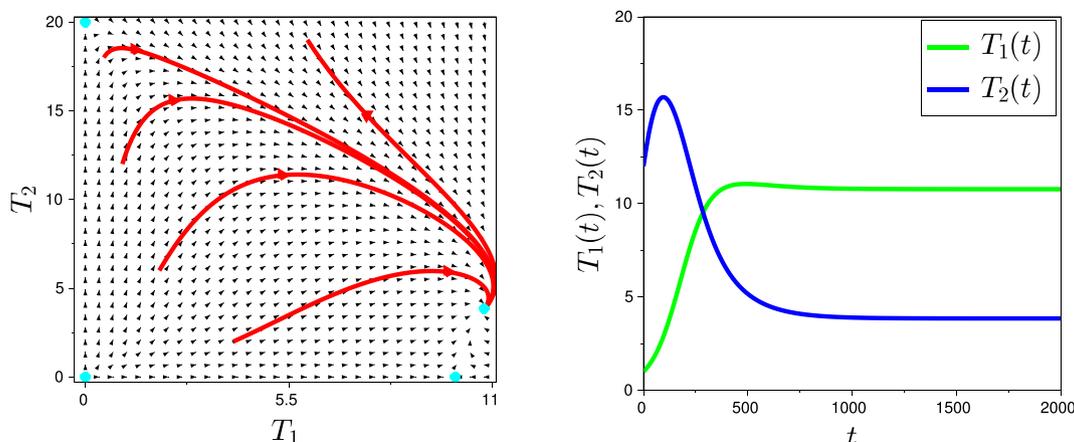


Fig. 8. Scenario (P2), where  $r_1 = 0.01, r_2 = 0.02, K_1 = 10, K_2 = 20, \alpha_{12} = -0.2$  and  $\alpha_{21} = 1.5$ .

of differential equations will be nonautonomous.

The three types of tourism interaction dynamics considered here can be placed in the Malaysian context. For example, competition dynamics can be observed in Langkawi and Penang Island. These tourism destinations are close to each other and tourists usually visit both sites. Both are popular beach destinations, with Penang Island focusing more on cultural aspects, heritage sites and local cuisine, while Langkawi offers great beaches, nice resorts and nature activities. Mutualism (or cooperation) is evident in the local tourism destinations within the state of Penang itself. Visitors to the mainland also explore the tourism sites in Penang Island (e.g. by crossing the bridge to visit heritage sites and enjoy the local cuisine of George Town). An example of predator-prey dynamics is seen in George Town ('predator') in the state of Penang and Ipoh ('prey') in the state of Perak. The Old Town in Ipoh has some similarities to George Town, one of the most popular sites to visit in Southeast Asia and was declared a UNESCO World Heritage Site in 2008. In Ipoh, travellers can feel the similarity to George Town when walking through the streets lined with ancient Chinese shop houses, street art and a variety of coffee shops with different themes. Not too many tourists visit the town except for the secluded historic streets. Although much quieter, Ipoh's Old Town does have the same vibe that makes George Town so popular. The only downside is that most businesses close after dark in Ipoh. Hence tourists spend more time in George Town.

More generally, the difference between competition and predator-prey dynamics can be subtle. We could consider two tourism destinations where one is 'more attractive' and the other 'less attractive'. The 'attractiveness' of Andergassen et al. (2013) a tourism destination can depend on many factors such as the number of interesting sites, geographical proximity etc. The 'more attractive' destination can be thought of as a 'predator' because it takes away visitors from the 'less attractive' destination (i.e. the 'prey'). For competition dynamics, both destinations can be thought of as being 'equally attractive'. The magnitudes of the interaction rates  $\alpha_{12}$  and  $\alpha_{21}$  can be used to quantify the 'attractiveness'. Predator-prey dynamics in (3.1) are characterised by opposite signs of  $\alpha_{12}$  and  $\alpha_{21}$ . For definiteness, if we assume the signs as in (P), then the first (respectively, second) tourism destination is the 'predator' (respectively, 'prey'). When  $|\alpha_{12}| \gg |\alpha_{21}|$ , then we can interpret this as the first destination being 'more attractive' than the second destination. Similarly, when  $|\alpha_{12}| \ll |\alpha_{21}|$ , this can be interpreted as the first destination being 'less attractive' than the second destination. Hence, defining an 'attractiveness ratio'  $A = |\alpha_{12}/\alpha_{21}|$ , it seems reasonable to say that the first destination is 'more attractive' (respectively, 'less attractive') than the second destination if  $A \gg 1$  (respectively,  $A \ll 1$ ). 'Equal attractiveness', as in the competition (C) and mutualism (M) cases, can be quantified through  $A \simeq 1$ .

Tourism is one of the tools of soft power for nation-states. Indeed, tourism contributes to the transmission of values and beliefs, as well as

to the projection of a particular image in the framework of nation-branding whereby the image that a country projects directly affects consumers' plans to visit that country (Anholt, 2007; Özkan & Boylu, 2021). Destinations are naturally in competition to attract tourists, hence their focus on image-building since it directly affects how people form their perceptions of a potential destination (Zeineddine & Nicolescu, 2018; Martens & Reiser, 2019; Duro, Pérez-Laborda, Turrión-Prats, & Fernández-Fernández, 2021). Anholt (2007) conceptualised this further by introducing the so-called competitive identity. This competitiveness between destinations is often evaluated through a series of statistical techniques aimed at quantifying inclusive competitiveness indicators (Gao, Shao, Chen, & Wei, 2021). Governments usually act as planners when it comes to nation-branding or city-branding, but competitiveness also results from a range of public-private partnerships and collaborations between different stakeholders (Zeineddine & Nicolescu, 2018).

As we have seen, the three patterns of competition, cooperation and predator-prey dynamics serve to characterise the actual interactions between tourism destinations. What is noticeable from a political and soft power perspective is that these interactions may serve to orient the branding narrative in a particular direction. Marketers at the entrepreneurial level and decision makers at the government level responsible for nation-branding also seek, through image-building, to control the narrative about these dynamics in order to ultimately ensure the attraction of their destination and its reputation.

As an example, the Gulf Cooperation Council (GCC) states are the most competitive tourism destinations in the region of the Middle East and North Africa, mostly due to their stability, which contrasts with the turmoil of other places in the region especially after the Arab Spring (Henderson, 2015). Dubai, in the popular imagination, is often defined as a city of superlatives with several icons reflecting this aspect: the tallest tower in the world, Burj Khalifa, unique artificial islands such as Palm Jumeirah, some of the biggest shopping malls and several festivals, notably the Dubai Shopping Festival in February/March (Sutton, 2016). Dubai's city-branding strategy started in the 1980s, materialising in several measures such as the creation of free zones and no-tax policies to attract investors (Gueraiche, 2019), ultimately translating into a blended image of ultra-modernity, luxury, consumerism and ultracapitalism.

While Dubai projects itself as a shopping, vibrant and busy destination of superlatives and architectural highlights, Abu Dhabi rather projects an image more associated with culture, museums and Emirati heritage, a quieter place than flashy Dubai, symbolised by the Sheikh Zayed Mosque (Lawton & Weaver, 2017; Martens & Reiser, 2019). This resulted between different stakeholders agreeing on the necessity for the city to differentiate itself from Dubai (Zeineddine & Nicolescu, 2018). Although Dubai is more identifiable than Abu Dhabi for foreign

observers, Dubai does not prey on Abu Dhabi. On the contrary, Abu Dhabi and Dubai are conceived as entities benefitting from each other rather than competitors (Martens & Reiser, 2019). In their study on the perceptions of German potential visitors to the UAE about Dubai and Abu Dhabi, Martens and Reiser (2019) found that the two destinations, despite their similar location and culture, were still able to create 'supplementary images in the minds of potential visitors', confirming the success of the marketing strategy. There are no indications of rivalry but a symbiotic relationship reinforcing their interdependence: while Abu Dhabi subsidises several of Dubai's governmental activities so it can focus on its diversification portfolio, Dubai endorses Abu Dhabi's prominence in political affairs and contributes to the wealth and job creation (Lawton & Weaver, 2017). As Dubai was reopening its borders in the summer of 2020 to tourists after closing them for four months due to the COVID-19 pandemic, the Executive Director of the Department of Culture and Tourism of Abu Dhabi, Ali AlShaiba, explicitly restated that the two emirates were not in competition with each other as they have been working together on complementary marketing campaigns including for the post-COVID era (Gibbon, 2020). If there is any form of competition, it rather takes place at the sub-brand level between different attractions and structures, including within each city (Lawton & Weaver, 2017; Martens & Reiser, 2019). This also echoes the finding of Romano (2016) about the inherently shifting nature of the interaction among destinations which can rarely be reduced to pure competition. Clearly, Abu Dhabi and Dubai's relationship is best understood along the lines of the cooperation (mutualism) pattern of interaction.

This 'supplementary images' branding could inspire other cities in the region to eventually coordinate their tourism strategies and create beneficial synergies for competitiveness (Lawton & Weaver, 2017). Dubai, by establishing a very competitive identity, has such an iconic image that the main challenge for other GCC competitors is to distinguish itself from this trendsetter (Govers, 2012; Zeineddine & Nicolescu, 2018). Inspiring a 'copycat' effect with subsequent heightened competition also implies that more innovation and distinctive niches are needed to stand out (Zeineddine & Nicolescu, 2018). If destinations envision the same type of service production, this can indeed lead to more similarity, less distinctiveness and ultimately more competition along the same spectrum of product (Butler & Weidenfeld, 2012).

Finally, the results of this article can also be interpreted from the viewpoint of economics. Each destination is a profit maximiser, profit being understood here as maximising the number of tourists which precisely depends on the tourist carrying capacity. Hence, because of mutualism (or cooperation), the tourist carrying capacities for both destinations are increased. In other words, a cooperative strategy allows agents (understood here as the respective destinations) to increase their respective payoffs (understood here as the flows of tourists). In the Stackelberg model, a firm (the leader) moves first based on advantages that allow it to make the first move, and the other firms (the followers) move sequentially (Askar, 2018). Therefore the firm-leader usually has a monopoly and the followers are the competitors (Askar, 2018). One of the values of the Stackelberg model is to allow for a better understanding of the 'persistence of market leadership and firms asymmetry within an industry' (Tesoriere, 2017, 102). In this configuration, 'the leader determines and announces its strategy first by anticipating the follower's reaction function, and the follower determines its strategy as a best response to the leader's strategy' (Al-Azzawi & Simaan, 2021, 86). In our framework, this oligopoly corresponds to a situation where a tourism destination has a dominant position. In economic terms, Porter (1998) established that a firm can expand its market share by adopting two strategies to dominate its rivals: create something that is unique with product differentiation or adopt economics of scale and invest in technological innovation to achieve cost leadership. Practically speaking, if this dominant tourism destination is able to divert flows of tourists, other destinations may precisely engage in strategies to differentiate themselves. Now, in reality, the interactions may be simultaneous, not necessarily sequential, thus limiting the predictive

power of a game depending on the situation. As an example, Godinho, Phillips, and Moutinho (2018, 13), in their study on the choice of hotel location between different competitors, noticed that 'we can consider that there is a simultaneous decision about which hotels to build, which typology to choose for each one and what prices to define. The final set of prices will constitute a Nash equilibrium, as usually considered in game theory, in which each hotel chooses a price that maximises its own profit'.

## 6. Conclusion

Interacting tourism destinations will go through different stages of development. An examination of each stage of development, as well as the speed of development, could provide indication of managerial actions for policy makers and resort managers. The effects of tourism activities in each development stage can provide tangible and intangible benefits to tourism stakeholders in all destinations. By having the information and understanding the trend of the tourism destination development in different stages, resort managers or policy makers can propose strategies to enhance the delivery of services, appropriate for each tourism destination, and ensure its survival. Good and effective guidelines could be created and can be adopted in the future to ensure that tourism development is sustainable and sensitive towards the local population.

Managerial methods and policies should evolve as the destinations experience different stages of development. Decision makers need metrics and forecasts to facilitate planning. The TALC model and its derivatives can guide sustainable tourism planning from that perspective (Kristjánsdóttir, 2015).

In this paper, we proposed an extension of the TALC model by considering two tourism destinations whose respective tourists exhibit interaction dynamics such as competition, mutualism (or cooperation) and predator-prey. We performed a qualitative analysis of the model in the same vein as Kristjánsdóttir (2015) for a single tourism destination. We investigated the stability of these steady states which could be reached under each respective pattern of interaction. Borrowing terminology from population ecology to characterise these equilibria and their stability, we found two instances of competitive exclusion and one instance of founder control under the pattern of competition dynamics. Conditions on the existence of a coexistence steady state were also determined for all three patterns of competition, mutualism and predator-prey. Under mutualism and predator-prey dynamics, when the coexistence steady state exists, it is always asymptotically stable. In relation to the TALC stages of development, we have observed that some aspects of the poststagnation stage, such as decline, may be better explained by viewing a tourism destination as part of a system of interacting tourism destinations rather than as a single entity. This confirms the relevance of redefining the concept of tourism destination in its ontology, as initiated in previous research (Candela & Figini, 2010; Andergassen et al., 2013; Chapman & Light, 2016).

A current work in progress is fitting the model (3.1) to actual tourist data to estimate the parameters. Following an integration-based approach that is especially useful for differential equation models (Holder & Rodrigo, 2013; Zulkarnaen & Rodrigo, 2020), it is possible to estimate the parameters  $r_1, r_2, K_1, K_2, \alpha_{12}$  and  $\alpha_{21}$  in (3.1). Then the appropriate interaction dynamics and scenario can be identified, which will aid in predicting what the tourist carrying capacities will be. For example, if after estimating the parameters it turns out that  $K_1 > \alpha_{12}K_2$  and  $K_2 > \alpha_{21}K_1$  (i.e. scenario (C3)), then it will be possible to forecast that eventually both tourist populations will reach a coexistence steady state with tourist population sizes whose values are those given by  $P_4$  in (3.4).

## CRedit authorship contribution statement

**M. Rodrigo:** Conceptualization, Methodology, Software, Validation,

Formal-analysis, Investigation, Resources, Writing-original-draft, Writing-review-editing, Visualization, Supervision, Project-administration. **I. Ajala:** Investigation, Resources, Writing-original-draft, Writing-review-editing. **A.K. Irhanida:** Investigation, Writing-review-editing.

interests or personal relationships that could have appeared to influence the work reported in this paper.

**Acknowledgement**

The authors are grateful for the support from the University of Wollongong through funding of a UOW Global Research Grant 2022.

**Declaration of competing interest**

The authors declare that they have no known competing financial

**Appendix A. Community matrix and eigenvalues**

The classification of the steady states of (3.1) follows from the analysis of the community matrix at any steady state  $(T_1, T_2)$ , namely

$$J(T_1, T_2) = \begin{pmatrix} r_1 - (2r_1/K_1)T_1 - (r_1\alpha_{12}/K_1)T_2 & -(r_1\alpha_{12}/K_1)T_1 \\ -(r_2\alpha_{21}/K_2)T_2 & r_2 - (2r_2/K_2)T_2 - (r_2\alpha_{21}/K_2)T_1 \end{pmatrix}.$$

We denote the eigenvalues of this matrix by  $\lambda_1$  and  $\lambda_2$ .

The eigenvalues of

$$J(P_1) = J(0, 0) = \begin{pmatrix} r_1 & 0 \\ 0 & r_2 \end{pmatrix}$$

are  $\lambda_1 = r_1$  and  $\lambda_2 = r_2$ .

The eigenvalues of

$$J(P_2) = J(K_1, 0) = \begin{pmatrix} -r_1 & -r_1\alpha_{12} \\ 0 & r_2(1 - \alpha_{21}K_1/K_2) \end{pmatrix}$$

are  $\lambda_1 = -r_1$  and  $\lambda_2 = r_2(1 - \alpha_{21}K_1/K_2)$ .

The eigenvalues of

$$J(P_3) = J(0, K_2) = \begin{pmatrix} r_1(1 - \alpha_{12}K_2/K_1) & 0 \\ -r_2\alpha_{21} & -r_2 \end{pmatrix}$$

are  $\lambda_1 = r_1(1 - \alpha_{12}K_2/K_1)$  and  $\lambda_2 = -r_2$ .

The analysis for  $P_4 = (T_{1,\infty}, T_{2,\infty})$  is a bit more involved. We see that

$$\begin{aligned} J(P_4) &= J(T_{1,\infty}, T_{2,\infty}) \\ &= \begin{pmatrix} r_1 - (2r_1/K_1)T_{1,\infty} - (r_1\alpha_{12}/K_1)T_{2,\infty} & -(r_1\alpha_{12}/K_1)T_{1,\infty} \\ -(r_2\alpha_{21}/K_2)T_{2,\infty} & r_2 - (2r_2/K_2)T_{2,\infty} - (r_2\alpha_{21}/K_2)T_{1,\infty} \end{pmatrix}. \end{aligned}$$

Using (3.3), we obtain

$$r_1 - \frac{2r_1}{K_1}T_{1,\infty} - \frac{r_1\alpha_{12}}{K_1}T_{2,\infty} = r_1 - \frac{r_1}{K_1}T_{1,\infty} - \frac{r_1\alpha_{12}}{K_1}T_{2,\infty} - \frac{r_1}{K_1}T_{1,\infty} = -\frac{r_1}{K_1}T_{1,\infty}$$

and

$$r_2 - \frac{2r_2}{K_2}T_{2,\infty} - \frac{r_2\alpha_{21}}{K_2}T_{1,\infty} = r_2 - \frac{r_2}{K_2}T_{2,\infty} - \frac{r_2\alpha_{21}}{K_2}T_{1,\infty} - \frac{r_2}{K_2}T_{2,\infty} = -\frac{r_2}{K_2}T_{2,\infty}.$$

Therefore

$$J(P_4) = J(T_{1,\infty}, T_{2,\infty}) = \begin{pmatrix} -(r_1/K_1)T_{1,\infty} & -(r_1\alpha_{12}/K_1)T_{1,\infty} \\ -(r_2\alpha_{21}/K_2)T_{2,\infty} & -(r_2/K_2)T_{2,\infty} \end{pmatrix}.$$

Denote the trace and determinant of  $J(P_4)$  by

$$\tau = \text{tr}(J(P_4)) = -\left(\frac{r_1}{K_1}T_{1,\infty} + \frac{r_2}{K_2}T_{2,\infty}\right),$$

$$\Delta = \det(J(P_4)) = \frac{r_1 r_2 (1 - \alpha_{12}\alpha_{21})}{K_1 K_2} T_{1,\infty} T_{2,\infty},$$

(A.1)

respectively. Hence the eigenvalues of  $J(P_4)$  are  $\lambda_1 = (\tau + \sqrt{\tau^2 - 4\Delta})/2$  and  $\lambda_2 = (\tau - \sqrt{\tau^2 - 4\Delta})/2$ . Moreover,

$$\begin{aligned} \tau^2 - 4\Delta &= \left(\frac{r_1 T_{1,\infty}}{K_1} + \frac{r_2 T_{2,\infty}}{K_2}\right)^2 - \frac{4r_1 r_2 (1 - \alpha_{12} \alpha_{21}) T_{1,\infty} T_{2,\infty}}{K_1 K_2} \\ &= \frac{r_1^2 T_{1,\infty}^2}{K_1^2} + \frac{2r_1 r_2 T_{1,\infty} T_{2,\infty}}{K_1 K_2} + \frac{r_2^2 T_{2,\infty}^2}{K_2^2} - \frac{4r_1 r_2 T_{1,\infty} T_{2,\infty}}{K_1 K_2} + \frac{4r_1 r_2 \alpha_{12} \alpha_{21} T_{1,\infty} T_{2,\infty}}{K_1 K_2} \\ &= \left(\frac{r_1 T_{1,\infty}}{K_1} - \frac{r_2 T_{2,\infty}}{K_2}\right)^2 + \frac{4r_1 r_2 \alpha_{12} \alpha_{21} T_{1,\infty} T_{2,\infty}}{K_1 K_2}. \end{aligned} \tag{A.2}$$

To investigate the eigenvalues further, we have to separate the analysis according to the type of interaction dynamics. Recall that  $P_1, P_2$  and  $P_3$  always exist under (C), (M) and (P). The existence of  $P_4$  will depend on the conditions as summarised in Table 1.

### A.1. Competition dynamics (C)

For  $J(P_1) = J(0, 0)$ , we see that  $\lambda_1 = r_1 > 0$  and  $\lambda_2 = r_2 > 0$ . Therefore  $P_1 = (0, 0)$  is an unstable node.

For  $J(P_2) = J(K_1, 0)$ , we have  $\lambda_1 = -r_1 < 0$  and  $\lambda_2 = r_2(1 - \alpha_{21}K_1/K_2)$ . Note that  $\lambda_2 < 0$  (respectively,  $\lambda_2 > 0$ ) if  $K_2 < \alpha_{21}K_1$  (respectively,  $K_2 > \alpha_{21}K_1$ ). Hence  $P_2 = (K_1, 0)$  is an asymptotically stable node if  $K_2 < \alpha_{21}K_1$  (i.e. (C1) or (C4)) and an unstable saddle point if  $K_2 > \alpha_{21}K_1$  (i.e. (C2) or (C3)).

For  $J(P_3) = J(0, K_2)$ , we have  $\lambda_1 = r_1(1 - \alpha_{12}K_2/K_1)$  and  $\lambda_2 = -r_2 < 0$ . Note that  $\lambda_1 < 0$  (respectively,  $\lambda_1 > 0$ ) if  $K_1 < \alpha_{12}K_2$  (respectively,  $K_1 > \alpha_{12}K_2$ ). Hence  $P_3 = (0, K_2)$  is an asymptotically stable node if  $K_1 < \alpha_{12}K_2$  (i.e. (C2) or (C4)) and an unstable saddle point if  $K_1 > \alpha_{12}K_2$  (i.e. (C1) or (C3)).

For  $J(P_4) = J(T_{1,\infty}, T_{2,\infty})$ , we know that  $\lambda_1 = (\tau + \sqrt{\tau^2 - 4\Delta})/2$  and  $\lambda_2 = (\tau - \sqrt{\tau^2 - 4\Delta})/2$ . From Table 1,  $P_4 = (T_{1,\infty}, T_{2,\infty})$  exists only if  $K_1 > \alpha_{12}K_2$ ,  $K_2 > \alpha_{21}K_1$  (i.e. (C3)) or  $K_1 < \alpha_{12}K_2, K_2 < \alpha_{21}K_1$  (i.e. (C4)). Therefore, under these two scenarios, (A.1) and (A.2) imply that  $\tau < 0$  and  $\tau^2 - 4\Delta > 0$ . We conclude that both  $\lambda_1$  and  $\lambda_2$  are real with  $\lambda_2 < 0$ . Furthermore,

$$T_{1,\infty} T_{2,\infty} = \frac{(K_1 - \alpha_{12}K_2)(K_2 - \alpha_{21}K_1)}{(1 - \alpha_{12}\alpha_{21})^2},$$

so that  $P_4 = (T_{1,\infty}, T_{2,\infty})$  will not exist for (C1) and (C2). For (C3),  $\alpha_{12} < K_1/K_2$  and  $\alpha_{21} < K_2/K_1$ , so that  $1 - \alpha_{12}\alpha_{21} > 0$ . Hence  $\Delta > 0$  in (A.1) and  $\lambda_1 < 0$ , concluding that  $P_4 = (T_{1,\infty}, T_{2,\infty})$  is an asymptotically stable node. Finally, for (C4),  $K_1/K_2 < \alpha_{12}$  and  $K_2/K_1 < \alpha_{21}$ . Thus  $1 - \alpha_{12}\alpha_{21} < 0$ , yielding  $\Delta < 0$  and  $\lambda_1 > 0$ , i.e.  $P_4 = (T_{1,\infty}, T_{2,\infty})$  is an unstable saddle point.

### A.2. Mutualism (or cooperation) dynamics (M)

For  $J(P_1) = J(0, 0)$ , we see that  $\lambda_1 = r_1 > 0$  and  $\lambda_2 = r_2 > 0$ . These imply that  $P_1 = (0, 0)$  is an unstable node.

For  $J(P_2) = J(K_1, 0)$ , we have  $\lambda_1 = -r_1 < 0$  and  $\lambda_2 = r_2(1 - \alpha_{21}K_1/K_2) > 0$  since  $\alpha_{21} < 0$ . This shows that  $P_2 = (K_1, 0)$  is an unstable saddle point.

For  $J(P_3) = J(0, K_2)$ , as  $\alpha_{12} < 0$ , we have  $\lambda_1 = r_1(1 - \alpha_{12}K_2/K_1) > 0$  and  $\lambda_2 = -r_2 < 0$ . Thus  $P_3 = (0, K_2)$  is an unstable saddle point.

Table 1 shows that  $P_4 = (T_{1,\infty}, T_{2,\infty})$  will not exist if  $1 - \alpha_{12}\alpha_{21} \leq 0$ . Assuming that  $1 - \alpha_{12}\alpha_{21} > 0$ , so that  $P_4 = (T_{1,\infty}, T_{2,\infty})$  exists, then (A.1) gives  $\tau < 0$  and  $\Delta > 0$ . These lead to  $\lambda_1 < 0$  and  $\lambda_2 < 0$ . Hence  $P_4 = (T_{1,\infty}, T_{2,\infty})$  is an asymptotically stable node when  $\alpha_{12}\alpha_{21} < 1$ .

### A.3. Predator-prey dynamics (P)

For  $J(P_1) = J(0, 0)$ , we see that  $\lambda_1 = r_1 > 0$  and  $\lambda_2 = r_2 > 0$ . We deduce that  $P_1 = (0, 0)$  is an unstable node.

For  $J(P_2) = J(K_1, 0)$ , we have  $\lambda_1 = -r_1 < 0$  and  $\lambda_2 = r_2(1 - \alpha_{21}K_1/K_2)$ . Note that  $\lambda_2 < 0$  (respectively,  $\lambda_2 > 0$ ) if  $K_2 < \alpha_{21}K_1$  (respectively,  $K_2 > \alpha_{21}K_1$ ). Hence  $P_2 = (K_1, 0)$  is an asymptotically stable node if  $K_2 < \alpha_{21}K_1$  (i.e. (P1)) and an unstable saddle point if  $K_2 > \alpha_{21}K_1$  (i.e. (P2)).

For  $J(P_3) = J(0, K_2)$ , since  $\alpha_{12} < 0$ , we have  $\lambda_1 = r_1(1 - \alpha_{12}K_2/K_1) > 0$  and  $\lambda_2 = -r_2 < 0$ . Therefore  $P_3 = (0, K_2)$  is an unstable saddle point.

From Table 1 we see that  $P_4 = (T_{1,\infty}, T_{2,\infty})$  will only exist if  $K_2 > \alpha_{12}K_1$ . Moreover,  $1 - \alpha_{12}\alpha_{21} > 0$  as  $\alpha_{12}\alpha_{21} < 0$ . Then (A.1) gives  $\tau < 0$  and  $\Delta > 0$ , which imply that  $\lambda_1 < 0$  and  $\lambda_2 < 0$ . Hence  $P_4 = (T_{1,\infty}, T_{2,\infty})$  is an asymptotically stable node.

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