TOURISM CARRYING CAPACITY AS A DYNAMIC PROPERTY OF COMPLEX SOCIO-ECOLOGICAL SYSTEMS

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January 27, 2026

Abstract

Overtourism is not just overcrowding: it is a systemic imbalance sustained by feedbacks between visitors, residents' welfare, the performance of local facilities, and environmental quality. Tourism carrying capacity sits at the centre of overtourism research and policy, yet it is still commonly operationalised as static visitor limits, implicitly assuming that thresholds could be set without accounting for the feedbacks they are meant to regulate. Here we introduce a minimal dynamical model that retains the essential feedbacks through which residents, tourists, economic capital, and environmental quality co-evolve. From this model, a formal definition of tourism carrying capacity emerges as a state-dependent quantity shaped by economic conditions, environmental quality, and social responses, and tempered by congestion and competitive pressure. Crucially, capacity alone is a weak planning target: sustainability depends on the long-run regime selected by the coupled system, and on how that regime shifts under perturbations. A bifurcation analysis of policy-relevant parameters maps tipping points and the resulting regime structure, from stable coexistence to multistability and sustained oscillations, including overtourism outcomes where tourism and capital persist while residents and environmental quality collapse. Overall, the results clarify, in a unified and rigorous setting, why capacity thresholds may inadequately reflect the dynamic complexity of tourism systems, and how integrated dynamical analyses can inform more robust policy design.

Keywords: tourism carrying capacity, tourism, socio-ecological modelling, non-linear systems, tipping points

1 Introduction

Tourism systems are complex socio-ecological systems in which visitors, residents, economic capital, and ecological resources interact continuously, generating nonlinear feedbacks that can either sustain desirable conditions or amplify degradation and abrupt changes [1–5]. This complexity underpins overtourism: not merely high numbers of visitors, but a systemic reorganisation of social, ecological, and infrastructural conditions under persistent pressure. Consequently, small shifts in residents' sensitivity to tourism, in how tourism revenues are reinvested locally, or in environmental pressure can qualitatively change long-run outcomes, shifting the system from sustainable coexistence to undesired states. Capturing these dynamics is necessary to move from impact accounting to mechanism-based governance and, crucially, to clarify the scope and limits of tourism carrying capacity when it is treated as a fixed threshold rather than as a property emerging from the coupled dynamics.

Accordingly, sustainability in tourism can be defined as the long-term persistence, within acceptable bounds, of the key social, ecological, and economic components of the system [1,6]. As a consequence, unsustainability is not a single outcome but may materialize through distinct regimes: environmental degradation, economic unprofitability, or social incompatibility; each corresponding to the loss of one dimension of the system [7, 8]. Building on this interpretation, overtourism can be seen as an unsustainable regime in which systemic pressures become socially salient, eroding residents' livability, degrading visitors' experience, and damaging the environment [6, 9].

While the term "overtourism" has gained prominence in recent years, the phenomenon it denotes is not new [10]. Its impacts span multiple externalities, including crowding in public spaces, noise and disturbances from inappropriate tourist behaviour, loss of local identity and amenities through physical touristification, displacement linked to short-term rentals such as Airbnb, and mounting pressure on urban and environmental services (waste management, water use, air quality) [11]. Crucially, these pressures are not only a function of absolute visitor numbers: they become socially salient when tourism intensity is high, often proxied by the tourist-to-resident ratio. As this ratio rises, residents face tighter access to housing and everyday services, higher costs, and a growing sense of loss of control over local life, which can trigger backlash against tourism, often framed as "tourismphobia" [12].

Its drivers combine income and population growth with declining travel and accommodation frictions, reinforced by digital exposure that concentrates flows on iconic places [13]. These forces have expanded and are expected to further intensify tourism pressures in the coming decades [14, 15], overloading specific sites from heritage cities to rural and island contexts [11,16]. Venice epitomizes this trajectory: sustained influxes have contributed to the progressive depopulation of the historic centre, widely referred to as the "Venice Syndrome", with similar tensions documented in Barcelona, Berlin, Paris, Amsterdam, and Florence [17]. Because residents' acceptance is a prerequisite for long-term tourism viability, these dynamics represent not only a social concern but also a systemic challenge to sustainability [18–20].

In response to such pressures, the concept of carrying capacity was progressively developed and adopted in tourism studies as a way to evaluate the limits beyond which visitor flows undermine environmental integrity, social acceptance, or economic viability. Originating in population ecology, the carrying capacity denoted the maximum population size that an environment could sustain indefinitely under competition for resources [21–23]. This "pure" ecological meaning — a structural limit imposed by resource constraints — provided the foundation for its later transposition into tourism, where it progressively acquired multidimensional interpretations [24, 25]. Early reflections on recreational saturation can be traced back to Sumner [26], and Wagar [27] provided the first formal application of carrying capacity to recreation management. In the 1980s, debates on the carrying capacity of tourist destinations advanced [28], to identify thresholds beyond which alterations caused by tourism activities become unacceptable for the overall system [29].

Over time, numerous definitions were proposed [30,31]; a widely cited formulation by the UNWTO defines carrying capacity as "the maximum number of people that may visit a tourist destination at the same time without causing destruction of the physical, economic or socio-cultural environment and an unacceptable decrease in the quality of tourist satisfaction" [14], implicitly suggesting a static threshold while highlighting three interdependent dimensions. The *physical* capacity refers to the pressure that an area can bear, encompassing both natural environments and built infrastructure. The *economic* capacity considers costs, benefits, and the income that tourism generates for local firms, residents, and the public sector. The *social* capacity measures the impacts of tourism on local communities, accounting for both residents' and tourists' perspectives [32–34]. In parallel, more practice-oriented frameworks were also developed to capture social responses to tourism growth: Doxey's Irridex [35] and Butler's Tourist Area Life Cycle (TALC) [36] illustrated how increasing visitor numbers could erode residents' acceptance and reduce destination attractiveness [11].

The carrying capacity framework thus offered a simple and practical tool for managers, providing reference thresholds for planning and monitoring. Yet, a central critique is that there is not a single carrying capacity: thresholds established by residents, tourists, and ecological systems may differ substantially [37,38]. Moreover, capacity cannot be reduced to the number of tourists alone, as factors such as behavior, timing, location, and type of use play equally critical roles [39]. This perspective clarifies that overtourism is not synonymous with mass tourism: some destinations can absorb large flows without severe impacts, while even modest increases elsewhere may trigger significant disruption [11]. It also highlights the importance of considering not only absolute numbers but also the proportion of tourists compared to residents as a key indicator to evaluate the social carrying capacity [40].

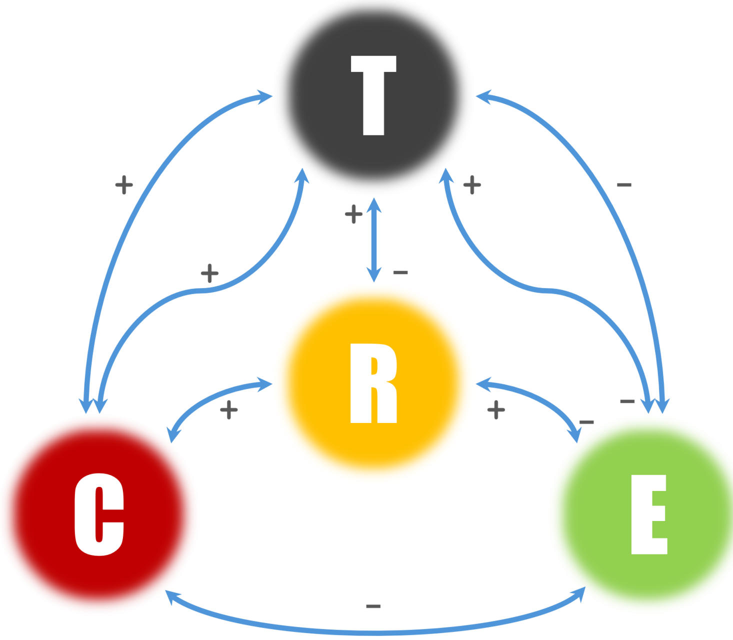

Figure 1: Conceptual scheme of the tourism-based socio-ecological system. The model includes four interacting components: Residents (R), Tourists (T), Capital (C), and Environment (E). Directed arrows represent causal influences. The sign shown next to each arrowhead (i.e., near the target variable) indicates the local effect of an increase in the source variable on the target: $+$ denotes a reinforcing effect, whereas $-$ denotes an inhibiting effect. The scheme extends the core triplet $\{T, E, C\}$ of Casagrandi and Rinaldi (2002) [1] by explicitly including residents as an endogenous component.

Despite its managerial appeal, the carrying capacity approach has been increasingly criticized for implicitly assuming linear and invariant system responses to growing pressures [11,18,29,34]. Carrying capacities may fluctuate under changing environmental and social conditions [41], and nonlinear feedbacks can trigger abrupt or irreversible transitions [3]. The Limits of Acceptable Change (LAC) framework [18,34,42] sought to address these issues by shifting attention from visitor numbers to observed impacts. However, LAC remains essentially static: it evaluates acceptability at a given point in time, but does not capture how dynamics unfold beyond critical thresholds or within evolving system structures [43].

These limitations call for approaches able to capture the dynamic, nonlinear behavior of tourism-based socio-ecological systems. Minimal or stylized models provide a powerful lens for this purpose [44–46]. By reducing the system to essential components and interactions, such models foreground the structural feedbacks that shape long-term trajectories, showing how simple mechanisms can generate complex behaviours, including oscillations, multistability, and abrupt regime shifts between alternative system states [3,47]. Their abstraction is therefore a strength: although not intended for operational management, they enable qualitative analysis of how parameter changes and feedback strengths shape emergent dynamics, while providing a conceptual foundation for more detailed, high-fidelity approaches [48,49]. Yet, tourism research has produced relatively few formal dynamical models (see, e.g., [19,50,51]), particularly those embedding residents endogenously within the coupled feedback structure linking social, economic, and environmental change.

In this study, we develop a four-variable minimal dynamical model linking Residents, Tourists, Environment, and Capital, grounded in the dynamical-systems tradition of tourism-based socio-ecological modelling [1,7,8,52–61]. Our key contribution is conceptual and analytical: by integrating, in a single formulation, the social, economic, environmental, and infrastructural channels commonly invoked in the carrying-capacity literature, the model yields a formal definition of tourism carrying capacity that follows from the system structure itself. Capacity thus emerges as a feedback-driven, state-dependent quantity: it co-evolves with the system, is uniquely defined within the model but inseparable from the other state variables that shape it, and is conditioned by the strength and configuration of the feedbacks governing long-run behaviour. Nevertheless, carrying capacity, taken in isolation, is not a sufficient sustainability target, since it does not by itself guarantee desirable long-run outcomes for residents, the environment, or capital. Our results provide decisive formal support to longstanding concerns in the literature that, even when capacity is defined in a rigorous, multidimensional, and state-dependent way, it remains a weak guide for planning and management if used on its own [27, 31, 41, 42, 62, 63]. Accordingly, we interpret carrying capacity as an informative descriptor rather than a stand-alone planning target, and adopt a dynamical-systems perspective to assess sustainability in an integrated way. Specifically, we propose bifurcation analysis as a qualitative tool for systemic assessment: by varying key structural parameters that represent policy-relevant interventions, we map how the coupled SES dynamics can reorganise, revealing coexistence, multistability, and oscillatory regimes in residents, tourism, environmental quality, and capital. In this setting, motivated by the Venetian case, we highlight residents' responses to tourism intensity as a central leverage mechanism shaping whether the system remains in a desirable regime or shifts toward overtourism outcomes.

2 Methods

To investigate the conditions under which sustainability or overtourism emerge, we extend the seminal minimal framework of Casagrandi and Rinaldi [1]. Their original model, built on the coupled dynamics of Tourists, Environment, and Capital, showed how nonlinear feedbacks among these components can generate alternative long-run regimes. Here we incorporate Residents as a fourth state variable, explicitly representing livability and social acceptance, which are central to overtourism dynamics [18, 33] yet often remain implicit in previous formulations. The resulting causal structure (Figure 1) captures the core feedbacks of a tourism-based socio-ecological system: tourists benefit from capital, environmental quality, and the presence of a resident community, while exerting pressures on both residents and ecosystems; residents contribute to capital and interact with the environment, but face welfare losses as tourism intensity rises; capital is sustained by the economic contributions of tourists and residents but depreciates in the absence of reinvestment; and the environment regenerates endogenously while being degraded by resident activity, tourism, and capital-related pressures.

2.1 Mathematical formulation

The mathematical model adopts a minimal and stylized formulation rooted in a long tradition of nonlinear dynamical systems used to study regime shifts in ecological and socio-ecological systems [3, 44]. Following this approach, the system is built from a small set of aggregated state variables and paradigmatic functional forms—logistic self-regulation, saturating Monod-Holling responses, and simple linear pressure terms—that have been shown to be sufficient to generate multistability, tipping points, and oscillatory dynamics [46]. This parsimony ensures that nonlinearity enters the model only where it is essential, allowing feedback structure rather than parameter complexity to drive the dynamics. Minimality is understood here in a structural sense: each state variable represents a pillar of sustainability (social, environmental, or economic), and removing any of them would prevent the model from explicitly representing that pillar and its associated feedbacks, thereby constraining the range of system-level regimes that can emerge. Within this framework, residents, tourists, capital, and the environment form the smallest closed system capable of expressing coexistence, collapse, and overtourism as alternative long-term attractors. The resulting formulation provides a transparent mathematical setting for interpreting carrying capacity as an endogenous, state-dependent property of the coupled dynamics, and for conducting illustrative bifurcation analyses.

The socio–ecological dynamics are represented by the following closed system of coupled nonlinear ordinary differential equations, which formalise the feedback structure described above:

$$
\begin{cases}
\dot{\mathbf{R}} = \mathbf{R}\left[\mu_{CR}\dfrac{\mathbf{C}}{\mathbf{C}+\phi_{CR}(\mathbf{T}+\mathbf{R})+\phi_{CR}} + \mu_{ER}\dfrac{\mathbf{E}}{\mathbf{E}+\phi_{ER}} - \alpha_R(\mathbf{R}+\mathbf{T}) - \omega\cdot\mathfrak{S}\left(\dfrac{\mathbf{T}}{\mathbf{R}}\right) - o\right] & (1)\\
\dot{\mathbf{T}} = \mathbf{T}\left[\mu_{CT}\dfrac{\mathbf{C}}{\mathbf{C}+\phi_{CT}(\mathbf{T}+\mathbf{R})+\phi_{CT}} + \mu_{ET}\dfrac{\mathbf{E}}{\mathbf{E}+\phi_{ET}} + \mu_{RT}\dfrac{\mathbf{R}}{\mathbf{R}+\phi_{RT}\mathbf{T}+\phi_{RT}} - \alpha_T(\mathbf{T}+\mathbf{R}) - a\right] & (2)\\
\dot{\mathbf{E}} = \mathbf{E}\left[r\left(1-\dfrac{\mathbf{E}}{K_E}\right) - \beta\mathbf{C} - \gamma\mathbf{T} - \theta\mathbf{R}\right] & (3)\\
\dot{\mathbf{C}} = -\delta\,\mathbf{C} + \varepsilon\,\mathbf{T} + \sigma\,\mathbf{R} & (4)
\end{cases}
$$

Each term in eqs. (1) to (4) represents a specific socio-ecological mechanism. The state variables $\mathbf{R}$, $\mathbf{T}$, $\mathbf{E}$, and $\mathbf{C}$ denote Residents, Tourists, Environment, and Capital. Each equation describes the net rate of change of one component as the balance between reinforcing and constraining processes. Positive terms represent benefits or inputs (e.g. revenues, natural regeneration, welfare), while negative terms represent pressures or losses (e.g. crowding, depreciation, environmental impacts). Collectively, these terms define a feedback architecture linking the social, economic, and ecological subsystems.

To retain analytical tractability while capturing all the mechanisms of interest, we use a small set of paradigmatic nonlinear response functions that capture the qualitative mechanisms of interest and preserve analytical tractability. Linear terms represent additive pressures proportional to the relevant driver (e.g. proportional environmental impacts or depreciation). Saturating benefits are represented through Hill functions,

$$
f(x) = \mu\,\frac{x^p}{x^p+\phi^p}, \qquad \mu > 0,\ \phi > 0,\ p \geq 1, \tag{5}
$$

where $f(x)$ is a bounded contribution of an effective resource x (e.g. capital per user, environmental quality) to growth or attractiveness. The parameter μ is the maximal contribution, ϕ is the half-saturation level (i.e. $f(\phi) = \mu/2$), and p controls curvature: larger p produces a more switch-like transition around ϕ. The Monod-Holling form used in the tourism and residents equations is the special case $p = 1$,

$$
f(x) = \mu\,\frac{x}{x+\phi}, \tag{6}
$$

which captures diminishing marginal returns with the simplest saturating structure.

Threshold-like social responses by residents are represented with a sigmoidal mapping $\mathfrak{S}(z)$ of an intensity variable z (here $z = \mathbf{T}/\mathbf{R}$). We assume $\mathfrak{S}$ is monotonically increasing, bounded, and satisfies $\lim_{z\to\infty}\mathfrak{S}(z) = 1$, with vanishing marginal sensitivity at both extremes, i.e. $\mathfrak{S}'(z) \to 0$ as $z \to 0$ and as $z \to \infty$. A parsimonious specification is the logistic function,

$$
\mathfrak{S}(z) = \left[1+\exp(-s(z-m))\right]^{-1}, \tag{7}
$$

where m is the inflection point and s controls steepness. This form yields a buffered region at low intensity, a rapid escalation around m, and saturation at high intensity.

Importantly, the results below do not hinge on any single functional choice: the state-dependent notion of tourism carrying capacity derived from the model follows from the coupled growth constraints implied by the feedback structure, and therefore remains qualitatively robust to alternative functional form specifications.

Residents $\dot{\mathbf{R}}$

For residents (eq. (1)), well-being, and thus the intrinsic attractiveness of remaining in the destination, increases with access to local capital and services and with environmental quality. Both channels enter through the saturating Monod-Holling response introduced above, capturing diminishing marginal benefits as conditions improve.

For the capital channel, we define the effective per-capita availability

$$
x_C = \frac{\mathbf{C}}{\mathbf{T}+\mathbf{R}+1},
$$

which treats capital and services as *rival* goods whose benefit is diluted by the total number of users [1]. The corresponding contribution to residents' well-being is then written as

$$\mu_{CR}\,\frac{x_C}{x_C+\phi_{CR}} = \mu_{CR}\frac{\mathbf{C}}{\mathbf{C}+\phi_{CR}(\mathbf{T}+\mathbf{R})+\phi_{CR}},$$

where μ_{CR} is the maximum attainable contribution of capital to residents' well-being and ϕ_{CR} is the half-saturation level. This formulation compactly represents benefit saturation under resource sharing effects, and makes explicit that residents' welfare depends on both the capital stock $\mathbf{C}$ and the competing demand generated by $\mathbf{T}+\mathbf{R}$.

Similarly, environmental quality provides an additional source of well-being for residents, reflecting the benefits associated with access to natural resources, clean surroundings, and a healthy ecosystem. The variable $\mathbf{E}$ is treated as a *public good*—non-rivalrous by definition—and is therefore not expressed in per-capita terms [1]. In this case, the argument of the Monod–Holling function in eq. (6) directly corresponds to the environmental state itself, yielding $\mu_{ER}\,\frac{\mathbf{E}}{\mathbf{E}+\phi_{ER}}$ The corresponding parameters μ_{ER} and ϕ_{ER} represent, respectively, the maximum contribution of environmental quality to residents' well-being and the half-saturation level of environmental benefits. Together, these two terms formalize how material (capital-based) and ecological (environmental) components jointly sustain residents' welfare through nonlinear, saturating relationships.

Crowding costs, represented by $-\alpha_R(\mathbf{R}+\mathbf{T})$, capture the effect of *tourism density*, i.e. the congestion generated by the absolute number of people sharing the same physical space and competing for local services, as in classical Verhulst-type formulations. This mechanism reflects pressures linked to space, mobility, and infrastructural load.

The additional nonlinear term $-\omega\cdot\mathfrak{S}(\mathbf{T}/\mathbf{R})$ instead captures *tourism intensity*, which depends on the relative abundance of tourists compared to residents. Intensity reflects a different mechanism from density: while density affects physical congestion, intensity shapes the social dimension of pressure, influencing residents' tolerance, perceptions, and sense of livability [18, 40, 64, 65]. This separation between density and intensity is well established in the literature. As argued by [66], density (tourists per unit area) and intensity (tourists per resident) operate through distinct channels and should not be conflated. The relevance of T/R as a proxy for social pressure was already recognized in early studies of carrying capacity [65], and is consistent with evidence that destinations with similar tourist volumes may experience overtourism very differently depending on their demographic base and spatial configuration [16]. This negative feedback is weak when tourism intensity is low, as residents can accommodate visitors without significant disruption to everyday routines [16]. As the tourist-to-resident ratio rises, however, social pressure accumulates: interactions become more intrusive, everyday life is increasingly disrupted, and residents report a growing sense of discomfort and loss of control over their living environment [12]. These forms of social saturation reinforce the feedback acting on the resident population.

Consistent with the qualitative properties stated above in eq. (7), we model residents' response to tourist intensity as a sigmoidal function of $z=\mathbf{T}/\mathbf{R}$:

$$\mathfrak{S}\left(\frac{\mathbf{T}}{\mathbf{R}}\right) = \left[1+\exp\left(-s\left(\frac{\mathbf{T}}{\mathbf{R}}-m\right)\right)\right]^{-1}. \tag{8}$$

For $\mathbf{T}/\mathbf{R}$ values below the inflection point m, the slope of the function, and thus the marginal effect of additional tourists, remains small, producing a buffering region where residents can accommodate moderate tourism pressure. As $\mathbf{T}/\mathbf{R}$ exceeds m, the slope steepens and social impacts escalate, until the function eventually saturates and approaches 1, reflecting the limited capacity of local communities to absorb further increases in tourism intensity.

In the resident equation eq. (1), this sigmoidal term is scaled by the parameter ω, which controls the overall strength of the social feedback. We treat ω as constant and specific to each socio-ecological system; alternatively, it may be regarded as a slowly varying exogenous parameter relative to the system's internal dynamics, so that the state variables evolve near quasi-equilibrium [67]. This assumption is central to the bifurcation analysis that follows.

The inclusion of a ratio-dependent term such as $\mathbf{T}/\mathbf{R}$ is consistent with a long and debated tradition in theoretical ecology. The contrast between prey- and ratio-dependent formulations—central to minimal ecological models of interacting populations—has been extensively discussed, most notably in the influential work of [68]. Within this framework, ratio-dependent terms are understood as simple but expressive representations of interaction intensity, suitable for minimal stylized models where the aim is to capture emergent system-level feedbacks rather than mechanistic details. Our formulation adopts this perspective: it preserves analytical tractability while conveying the essential phenomenology of the social–ecological coupling between tourism pressure and residents' response.

It should also be noted that the influence of tourism on residents is not purely negative. Its positive effects are, however, mostly indirect: tourists contribute to residents' well-being through the economic capital generated by tourism-related activities—employment, business opportunities, and fiscal revenues—that can enhance local welfare and sustain public services. This indirect contribution is explicitly represented in the capital equation discussed below. Hence, the feedback encapsulated in the model represents a net social response, emerging from the balance between the positive economic externalities of tourism and its negative social and environmental externalities. Finally, an exogenous demographic term $-o$ accounts for long-term trends such as aging or migration that shape livability independently of tourism.

Tourists $\dot{\mathbf{T}}$

Tourist dynamics (eq. (2)) follow a destination-attractiveness formulation in which net inflow is proportional to $\mathbf{T}$ times the perceived relative attractiveness of the site [1]. We represent this as a per-capita balance between reinforcing attractiveness components and crowding or competition costs. As in the resident formulation, reinforcing components are expressed through saturating Monod-Holling terms. Environmental quality enhances attractiveness via $\mu_{ET}\,\dfrac{\mathbf{E}}{\mathbf{E}+\phi_{ET}}$, whereas capital and services contribute through a rival, congestion-sensitive channel $\mu_{CT}\,\dfrac{\mathbf{C}}{\mathbf{C}+\phi_{CT}(\mathbf{T}+\mathbf{R})+\phi_{CT}}$, as in the resident equation, so that the effective benefit of a given capital stock is shared among more users as total visitation increases.

A third contribution captures cultural and social authenticity [69], i.e. the idea that as destinations adapt to sustained high flows and crowding, core on-site experiences may be perceived as less authentic, with downstream effects on satisfaction and behavioural intentions such as revisiting and recommending [70]. In the Monod-Holling form eq. (6), we set

$$x = \frac{\mathbf{R}}{\mathbf{T}+1},$$

so that authenticity increases with the resident base but becomes less available per visitor as tourism intensity rises. This yields

$$\mu_{RT}\,\frac{x}{x+\phi_{RT}} \;=\; \mu_{RT}\,\frac{\mathbf{R}}{\mathbf{R}+\phi_{RT}\mathbf{T}+\phi_{RT}},$$

making explicit that the cultural "signal" provided by residents is strongest when $\mathbf{R}$ is large relative to $\mathbf{T}$, and progressively weakens as tourists outnumber residents, consistent with narratives on the "Venice Syndrome" [17]. In this representation, μ_{RT} encodes the average weight assigned to authenticity in tourist demand, while ϕ_{RT} controls the intensity level at which this component attenuates; together, they provide an aggregate (mean-field) representation of heterogeneity in visitor preferences and perceptions.

These attractiveness channels are counteracted by density-related disutility and a baseline competitiveness term, represented in eq. (2) by $-\alpha_T(\mathbf{T}+\mathbf{R})$ and $-a$, respectively. The latter term represents the *absolute average utility* of potential tourist destinations; accordingly, all other components in the square brackets of eq. (2) can be interpreted as *relative utilities* measured against this baseline. Equivalently, the bracketed term is a utility differential $[A-a]$, where A aggregates the positive contributions of environment, capital, and residents' cultural endowment, net of congestion effects, and a is the competition benchmark. This interpretation aligns with the notion of tourism flows being guided by perceived net benefits relative to outside options rather than absolute levels of attractiveness [1].

We do not include an additional ratio-dependent social-feedback term in the tourist equation: tourists are modelled as transient visitors who primarily respond to their own abundance directly through the density-related crowding cost, and otherwise only indirectly through the state variables that define contemporaneous attractiveness A (capital, environment, and resident-based authenticity). Residents, by contrast, encode cumulative exposure through slower adjustment processes—fatigue, protest, and exit—which motivates the ratio-dependent term $\mathfrak{S}(\mathbf{T}/\mathbf{R})$ in eq. (1).

Finally, note that our formulation of residents and tourists reflects the view that destinations combine objective conditions with subjective dimensions such as tourist and resident perceptions [29, 71]. In this minimal model, these subjective components enter in aggregated (mean-field) form through the response parameters (e.g. $\mu, \phi, \omega, \alpha$), which summarise how perceptions and behavioural tendencies translate a given system state into experienced attractiveness and social pressure.

Environment $\dot{\mathbf{E}}$

Environmental dynamics (eq. (3)) combines endogenous regeneration with anthropogenic pressures. Natural recovery follows a logistic law $r(1 - \mathbf{E}/K_E)$, whereas degradation is modelled, in first-order approximation, as a linear combination of three stressors: pressure from capital, $-\beta\,\mathbf{C}$, from tourists, $-\gamma\,\mathbf{T}$, and from residents, $-\theta\,\mathbf{R}$. This specification implies that one component of environmental pressure scales directly with tourists and residents (e.g., waste generation, water consumption, or energy use for mobility and accommodation), while another scales with capital (e.g., operation and maintenance of facilities, transportation infrastructure, or energy-intensive services such as cooling, lighting, and other service provision) [1]. More nonlinear damage mechanisms could be introduced, but the present form isolates how the feedback structure, rather than parameter proliferation, organises the long-run regimes analysed below. We consistently take β, γ and θ as positive, interpreting these coefficients as degrading effects under typical use patterns. More generally, they can be interpreted as reduced-form *net* impact parameters: if tourism is linked to restoration or stewardship programmes, if residents' practices systematically reduce local pressures, or if the capital stock reflects green infrastructure and nature-based facilities that enhance ecosystem functioning (e.g. habitat restoration, wastewater treatment upgrades, low-impact mobility or mitigation investments), the corresponding effective pressures can be reduced and may even become negative (i.e. $\beta < 0$, $\gamma < 0$, and/or $\theta < 0$), indicating a positive contribution to environmental quality.

Capital $\dot{\mathbf{C}}$

Capital dynamics (eq. (4)) follow the stock-flow structure introduced by Casagrandi and Rinaldi [1] and can be read as a reduced-form perpetual-inventory mechanism:

$$\dot{\mathbf{C}} = -\delta\,\mathbf{C} + \varepsilon\,\mathbf{T} + \sigma\,\mathbf{R}.$$

The term $-\delta\,\mathbf{C}$ captures depreciation and obsolescence of facilities, services, and infrastructure, while the inflows $\varepsilon\,\mathbf{T}$ and $\sigma\,\mathbf{R}$ represent, in aggregate form, maintenance and reinvestment financed by tourism-related expenditure and by resident-based economic activity, respectively. This parsimonious specification links the evolution of the capital stock to both external demand (tourism) and internal support (residents), making explicit that sustained profitability and service provision require sufficient reinvestment.

Crucially, carrying capacity is not imposed as an external limit in this formulation; it is an endogenous, state-dependent object that can be derived from the coupled dynamics, through the effective growth constraints generated by the interacting subsystems.

2.2 Tourism Carrying Capacity

Overall, the system in eqs. (1) to (4) embeds the three pillars of sustainability—environmental, economic, and social—within a unified dynamical system. By assigning explicit functional forms to each factor, the model translates qualitative notions such as crowding, authenticity, and tourism intensity into operational terms that can be analysed with the tools of dynamical systems theory.

We first derive tourism carrying capacity in a general dynamical setting, and then specialise the definition to our four-dimensional Residents–Tourists–Environment–Capital system in eqs. (1) to (4). We start from the broad class of destination-attractiveness dynamics discussed above, in which the net change in visitors is proportional to the current tourist stock and to a composite, state-dependent per-capita *attractiveness* signal. Formally,

$$\dot{\mathbf{T}} = \mathbf{T} \cdot g(\mathbf{T}, \mathbf{Y}), \tag{9}$$

where g denotes the per-capita net growth rate of tourists, interpreted here as an aggregate attractiveness differential, and $\mathbf{Y}$ collects all remaining socio-ecological variables shaping attractiveness (e.g., residents, capital and environmental quality).

In this framework, tourism carrying capacity is identified with a strictly positive *asymptotically stable* equilibrium of eq. (9), namely a visitation level to which $\mathbf{T}(t)$ converges and that is restored after sufficiently small perturbations. By definition, equilibria satisfy $\dot{\mathbf{T}} = 0$ (i.e. no change over time); from eq. (9) this can occur either at the *trivial* equilibrium $\mathbf{T} = 0$ or, for a *non-trivial* equilibrium $\mathbf{T}^* > 0$, when

$$g(\mathbf{T}^*, \mathbf{Y}) = 0.$$

At this stage we do not impose any specific functional form on g, and therefore the existence, location, and multiplicity of positive roots cannot be taken for granted. Our objective is thus to identify general, interpretable conditions under which eq. (9) admits a *unique* positive equilibrium for a given socio-ecological state $\mathbf{Y}$, so that tourism carrying capacity can be defined unambiguously within this general attractiveness-based representation.

Let $\mathbf{Y}$ be a given admissible socio-ecological state and consider the induced one-dimensional map $\mathbf{T} \mapsto g(\mathbf{T} \mid \mathbf{Y})$. We then define the *tourism carrying capacity* as the (state-dependent) positive visitation level $K_T(\mathbf{Y})$ satisfying

$$g(K_T(\mathbf{Y}); \mathbf{Y}) = 0, \qquad K_T(\mathbf{Y}) > 0, \tag{10}$$

whenever such a solution exists. Importantly, eq. (10) defines an instantaneous, state-contingent object: it is specified pointwise in the state space and therefore does not require $\mathbf{Y}$ to be constant over time.

We next provide simple sufficient conditions ensuring that, for any given socio-ecological state $\mathbf{Y}$, such a state-dependent carrying capacity exists and is unique, and we then discuss the main properties that follow.

Sufficient conditions for existence and uniqueness

We write $g(\mathbf{T}|\mathbf{Y})$, to indicate that the value of $\mathbf{Y}$ is given throughout.

Assumption 1 (Existence condition – Sign change) *The destination is attractive when visitation is negligible, but congestion and other disutilities dominate at sufficiently high visitation, so that net tourist growth eventually becomes negative. Formally, we assume*

$$g(0|\mathbf{Y}) > 0 \qquad \textit{and} \qquad \exists\, \mathbf{tildeT} > 0 : \; g(\tilde{\mathbf{T}}|\mathbf{Y}) < 0.$$

Assumption 2 (Uniqueness condition – Strict monotonicity in T)) *Additional visitation should reduce net tourist growth. Formally, we assume that $g(\cdot|\mathbf{Y})$ is continuous on $[0, \infty)$, differentiable on $(0, \infty)$, and strictly decreasing in $\mathbf{T}$, i.e.*

$$\frac{\partial g(\mathbf{T}|\mathbf{Y})}{\partial \mathbf{T}} < 0 \qquad \textit{for all } \mathbf{T} > 0.$$

Proposition 1 (Existence and uniqueness of the carrying capacity) *Under Assumptions 1 and 2, there exists a unique $K_T(\mathbf{Y}) > 0$ solving eq. (10). Moreover, for any $\mathbf{T} > 0$,*

$$\mathbf{T} < K_T(\mathbf{Y}) \;\Rightarrow\; \dot{\mathbf{T}} > 0, \qquad \mathbf{T} > K_T(\mathbf{Y}) \;\Rightarrow\; \dot{\mathbf{T}} < 0. \tag{11}$$

Then we call the quantity $K_T(\mathbf{Y})$ tourism carrying capacity*.*

Equation eq. (11) states that tourist visitation increases when $\mathbf{T}$ is below $K_T(\mathbf{Y})$ and decreases when $\mathbf{T}$ exceeds it. In this sense, $K_T(\mathbf{Y})$ acts as a state-dependent threshold separating positive from negative net inflow, capturing the defining qualitative property of a carrying capacity within the tourist subsystem.

Proof 1 (Proof (sketch)) *By continuity and the sign change in Assumption 1, the intermediate value theorem guarantees the existence of at least one root on $(0, \tilde{\mathbf{T}})$. Strict monotonicity in Assumption 2 rules out multiple roots, hence the solution $K_T(\mathbf{Y})$ is unique (see figure 2). Finally, since $\dot{\mathbf{T}} = \mathbf{T} \cdot g(\mathbf{T})$ and $\mathbf{T} > 0$, the sign of $\dot{\mathbf{T}}$ coincides with the sign of $g(\mathbf{T})$, which yields eq. (11).* □

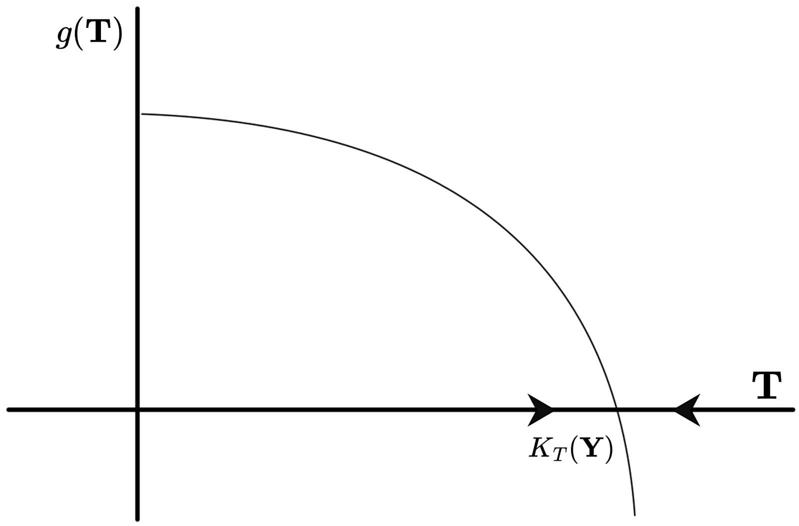

Figure 2: Illustrative per-capita tourist growth function $g(\mathbf{T} \mid \mathbf{Y})$ satisfying Assumptions 1–2. The unique positive root defines the tourism carrying capacity $K_T(\mathbf{Y})$. Arrows indicate the direction of motion of $\mathbf{T}$ implied by eq. (9): increases where $g > 0$ and decreases where $g < 0$.

A broader discussion of the generality of these assumptions is provided in Appendix A.

In summary, a well-defined state-dependent carrying capacity $K_T(\mathbf{Y})$ emerges under two very general requirements: (i) net attractiveness is positive at low visitation but becomes negative at sufficiently high visitation, and (ii) net attractiveness is strictly decreasing in visitation for fixed socio-ecological conditions $\mathbf{Y}$, i.e. marginal disutilities dominate marginal benefits in the partial effect $\partial/\partial\mathbf{T}$. Importantly, this does not imply that attractiveness declines as the overall system improves: changes in $\mathbf{Y}$ (e.g. higher environmental quality $\mathbf{E}$ or capital $\mathbf{C}$) can increase $K_T(\mathbf{Y})$. This dependence on $\mathbf{Y}$ is precisely what makes carrying capacity dynamic: it moves with the evolving socio-ecological state and with external forcings acting on the system.

Because eq. (10) is defined pointwise in state space, allowing $\mathbf{Y}$ to evolve does not undermine the existence-and-uniqueness result. Rather, the dynamics of $\mathbf{Y}$ determine *where* along a trajectory the conditions for a well-defined capacity hold, and thus whether K_T is defined at each instant. In particular, carrying capacity becomes a moving target,

$$K_T(t) := K_T\big(\mathbf{Y}(t)\big),$$

which remains *unique at each time* as long as $\mathbf{Y}(t)$ stays within the region where Assumptions 1–2 are satisfied.

The tourism carrying capacity from the SES model

The tourist equation in eq. (2) is a particular instance of eq. (9), where $g(\mathbf{T}|\mathbf{Y}) = g(\mathbf{T}|\mathbf{R}, \mathbf{E}, \mathbf{C})$. In our formulation, attractiveness benefits are built from bounded, saturating Monod-Holling components (environment, capital and services, resident-based authenticity), while disutilities include a crowding term that increases without bound in $\mathbf{T}$ and a competition benchmark a. Consequently, for any fixed $(\mathbf{R}, \mathbf{C}, \mathbf{E})$ with positive resources, the resulting per-capita rate is continuous and strictly decreasing in $\mathbf{T}$, and it becomes negative for sufficiently large $\mathbf{T}$. Hence, the system satisfies the sufficient conditions above and admits a unique state-dependent tourism carrying capacity $K_T(\mathbf{R}, \mathbf{C}, \mathbf{E})$ as defined by eq. (10) (see Appendix B for details).

Notably, keeping residents, environment and capital fixed (i.e. conditioning on $\mathbf{Y} = (\mathbf{R}, \mathbf{C}, \mathbf{E})$), the tourist equation eq. (2) can be rearranged, after some simple algebraic passages, into a logistic-type identity,

$$\dot{\mathbf{T}} = \rho_T(\mathbf{T}, \mathbf{Y})\, \mathbf{T} \left(1 - \frac{\mathbf{T}}{K_{\text{eff}}(\mathbf{T}, \mathbf{Y})}\right), \tag{12}$$

where ρ_T collects the bounded attractiveness components (minus the competition) and K_{eff} is the corresponding density-dependent scale:

$$\rho_T(\mathbf{T},\mathbf{Y}) = \overbrace{\mu_{CT}\,\frac{\mathbf{C}}{\mathbf{C}+\phi_{CT}(\mathbf{T}+\mathbf{R})+\phi_{CT}}}^{\text{Economic}} + \overbrace{\mu_{ET}\,\frac{\mathbf{E}}{\mathbf{E}+\phi_{ET}}}^{\text{Environmental}} + \overbrace{\mu_{RT}\,\frac{\mathbf{R}}{\mathbf{R}+\phi_{RT}\mathbf{T}+\phi_{RT}}-\alpha_T\,\mathbf{R}-a}^{\text{Social}}, \tag{13}$$

$$K_{\text{eff}}(\mathbf{T},\mathbf{Y}) = \frac{\rho_T(\mathbf{T},\mathbf{Y})}{\underbrace{\alpha_T}_{\text{Infrastructural}}}\,. \tag{14}$$

This decomposition makes explicit the canonical dimensions of carrying capacity discussed in the literature (see e.g. [14, 34, 72, 73]. Importantly, tourism carrying capacity in our model is not imposed by assuming a logistic law: it follows from the general attractiveness formulation and is defined as the unique positive root $K_T(\mathbf{Y})$ of $g(\mathbf{T} \mid \mathbf{Y}) = 0$ under Assumptions 1–2 (see also Appendix B). Equation eq. (12) is therefore only a convenient rearrangement that makes the contributing channels transparent by introducing an effective scale $K_{\text{eff}}(\mathbf{T},\mathbf{Y}) = \rho_T(\mathbf{T},\mathbf{Y})/\alpha_T$; in particular, at $\mathbf{T} = K_T(\mathbf{Y})$ we have $g = 0$, hence $\mathbf{T} = K_{\text{eff}}(\mathbf{T},\mathbf{Y}) = K_T(\mathbf{Y})$.

A key implication is that carrying capacity is not treated as an externally set ceiling: it is implied by the same feedback structure that governs the joint evolution of residents, capital, and the environment. Capacity is therefore a dynamic, state-dependent constraint that can be analysed with dynamical-systems tools. Importantly, however, it is an instantaneous growth condition ($\dot{\mathbf{T}} = 0$) given $(\mathbf{R},\mathbf{E},\mathbf{C})$, not a guarantee of long-run sustainability: in nonlinear regimes with multistability and hysteresis, the same tourist level can be associated with qualitatively different outcomes depending on the basin of attraction and the trajectory. This motivates the bifurcation analysis below as a systematic way to map regime structure and tipping points in the coupled system.

2.3 Bifurcation analysis

The uniqueness of $K_T(\mathbf{R},\mathbf{C},\mathbf{E})$ should not be conflated with uniqueness of the long-run tourism level of the full coupled system. Feedbacks among $(\mathbf{R},\mathbf{T},\mathbf{E},\mathbf{C})$ can generate multistability or sustained oscillations, implying that different attractors may coexist and that $\mathbf{T}(t)$ need not converge to a constant even when $K_T(t)$ is well-defined at all times. The definition eq. (10) therefore isolates an instantaneous growth constraint, rather than prescribing a unique long-run visitor level.

Accordingly, although $K_T(\mathbf{Y})$ is uniquely defined (whenever Assumptions 1–2 hold), the coupled system may admit multiple attractors, so that long-run outcomes depend on both parameters and initial conditions. We therefore use bifurcation analysis to map how the qualitative regime structure of eqs. (1) to (4) reorganises under slow variations in key parameters. In this context, an *equilibrium* (or fixed point) is a stationary state $(\mathbf{R}^*,\mathbf{T}^*,\mathbf{E}^*,\mathbf{C}^*)$ satisfying

$$\dot{\mathbf{R}} = \dot{\mathbf{T}} = \dot{\mathbf{E}} = \dot{\mathbf{C}} = 0,$$

so that all state variables remain constant in time. The *local stability* of an equilibrium is determined by the linearisation of the vector field: letting $J(\mathbf{R}^*,\mathbf{T}^*,\mathbf{E}^*,\mathbf{C}^*)$ denote the Jacobian matrix, the equilibrium is *(locally) asymptotically stable* if sufficiently small perturbations decay and trajectories return to $(\mathbf{R}^*,\mathbf{T}^*,\mathbf{E}^*,\mathbf{C}^*)$ as time progresses, which holds when all eigenvalues of J have negative real parts. Conversely, the equilibrium is *unstable* if arbitrarily small perturbations can grow and drive the state away, which occurs when at least one eigenvalue of J has positive real part. Beyond equilibria, nonlinear systems may also admit stable *periodic orbits* (limit cycles), quasi-periodic motion on invariant tori, or, in principle, chaotic attractors, as well as long transients near unstable invariant sets.

These definitions address *dynamical* (local) stability: they describe the response of trajectories to small perturbations while the governing equation of motions are held fixed. They therefore speak to questions such as whether a perturbation to one or more of the four state variables is followed by a return toward the same state (stability), how rapidly this relaxation occurs, or whether the perturbation instead drives the trajectory away from that regime. *Structural* stability, instead, concerns the robustness of the *qualitative* organisation of the dynamics (e.g. the presence and type of equilibria, cycles, or multistability) under small changes in parameters or, more broadly, small modifications in the interaction mechanisms. In practical terms, it asks whether gradual shifts in slow controls, such as residents' tolerance to tourism intensity (modelled by ω), external competitiveness (captured by a), or the strength of the tourism-to-capital reinvestment channel (set by ε), translate into comparably gradual changes in long-run levels, or whether they can instead produce abrupt reorganisations of the regime structure, for example by pushing the system into a different long-run condition (such as resident persistence versus depopulation), or by turning a steady state into recurrent boom–bust fluctuations. In other words, dynamical stability is about how trajectories react to small shocks *within* a given model, whereas structural stability is about how the set of possible long-term regimes changes *across* nearby models as parameters shift.

Policies can affect the system through two conceptually distinct channels. First, they may act as *state perturbations* that alter the trajectory without changing the governing feedback structure, by inducing abrupt changes in one or more state variables (access restrictions, sudden infrastructure disruptions, one-off restoration actions). In multistable settings, such perturbations can shift the system across the boundary between "basins of attraction" of different equilibria, so that the long-run outcome changes even though the underlying dynamical system remains structurally identical. Second, policies may induce *structural changes* by modifying the strength or balance of feedbacks. In our formulation, these structural drivers enter through a set of model parameters. For the purpose of bifurcation analysis, parameters are treated as constant on the fast timescale of the internal dynamics, but they can be interpreted as slowly varying controls (reflecting policy, institutions, or socio-cultural conditions) that move the system through a family of nearby dynamical regimes.

Under this quasi-static view of policy as a structural driver, slowly tuning a parameter can bring the system to critical thresholds at which structural stability changes. We refer to these thresholds as bifurcation *tipping points*: values of a control parameter at which an equilibrium (or more generally an attractor) is created or destroyed, or its stability changes. As a result, the long-run dynamics can reorganise abruptly, because trajectories that previously relaxed back to a given regime can no longer do so and are instead redirected toward a different attractor. We visualise these transitions with *bifurcation diagrams*, which plot the equilibrium levels of the state variables against the chosen control parameter and indicate stability, so that regime shifts and multistability domains can be read directly from the structure of the branches. Operationally, we compute these diagrams via *codimension-one continuation*, which tracks equilibria (and, when present, periodic orbits) as a single control parameter varies, distinguishing stable and unstable branches and automatically detecting the critical points at which existence or stability changes. In the diagrams, bifurcation points are indicated by special markers. In particular, *limit points* (LP, also known as fold or saddle–node bifurcations) occur when a stable and an unstable equilibrium branch collide and are created or annihilated, producing the turning points that delimit bistable intervals. *Branch points* (BP) mark locations where an equilibrium loses uniqueness and a secondary equilibrium branch emerges (or merges), indicating a change in the branching structure of the solution set.

To assess interactions among drivers, we also perform codimension-two continuations by varying pairs of parameters (e.g. (ω, ε) or (ω, β)) and continuing loci of fold and Hopf points across the parameter plane. This reveals organising centres such as cusp points, Bogdanov–Takens points and generalized Hopf (Bautin) points, which partition parameter space into regions with distinct asymptotic behaviour (single versus multiple equilibria, steady versus oscillatory regimes). For a general introduction to nonlinear dynamical systems and bifurcation analysis, the reader is referred to standard texts such as [47].

The parameters we vary have direct economic and socio-ecological interpretations. The parameter ε controls the per-capita contribution of tourism to the capital stock $\mathbf{C}$, capturing how strongly tourist activity translates into effective maintenance and reinvestment. Increasing ε strengthens the reinforcing loop between tourism, capital, and destination attractiveness, and can therefore shift the system from smooth adjustment to overshoot-like responses when social or environmental constraints become binding. The parameter ω scales the intensity-driven social-pressure term $-\omega\, \mathfrak{S}(\mathbf{T}/\mathbf{R})$ in eq. (1), summarising how strongly residents react to tourism intensity: higher ω corresponds to lower tolerance and stronger resident outflow at a given $\mathbf{T}/\mathbf{R}$. Finally, β, γ, θ regulate environmental pressures in eq. (3) exerted by capital, tourists, and residents, respectively, and therefore control how rapidly environmental quality erodes for a given socio-economic configuration.

Motivated by the Venetian case, which has experienced a long-run decline in the resident population of the historic centre alongside sustained tourism pressure, we focus on ω as a central control parameter. In Venice, tourism pressure is often perceived in terms of high *tourism intensity*: the resident base is small relative to the visitor stock, so the tourist-to-resident ratio can rise sharply and translate into tangible losses in quality of life. This makes the social burden particularly sensitive to $\mathbf{T}/\mathbf{R}$, so that the intensity channel captured by $\omega\,\mathfrak{S}(\mathbf{T}/\mathbf{R})$ is a natural organiser of the regime structure. While treated as constant over the fast system dynamics, ω can be interpreted as a slowly drifting quantity on policy and socio-cultural time scales, reflecting gradual changes in institutions, norms, and cumulative exposure.

All continuation results were obtained with *MatCont* [74]. The continuation outputs were exported and post-processed in **R** to produce the figures; baseline parameter values are reported in Appendix Table 1. Standard references for the theory and numerical practice of these methods include [47, 75, 76].

3 Results

In the following, we present one–parameter continuation diagrams for key drivers of the dynamics. Each diagram illustrates how equilibrium branches evolve under changing conditions, which state variables persist or vanish, and how these transitions can be interpreted. We begin with the analysis of the social–pressure parameter ω, which controls the strength of the ratio–dependent social–pressure term $-\omega\,\mathfrak{S}(\mathbf{T}/\mathbf{R})$ in the resident dynamics.

Since "overtourism" is commonly discussed as a phenomenon that becomes salient through host-community responses and social acceptability constraints [11, 77], we interpret ω as an aggregate measure of social sensitivity to changes in tourism intensity, proxied here by the tourist-to-resident ratio. This does not imply that overtourism concerns residents alone: crowding and experience degradation may also bind on the visitor side. In our minimal formulation, however, the $\omega\,\mathfrak{S}(T/R)$ channel captures the resident-facing component of social pressure that is especially relevant in heritage cities with a limited resident base, such as Venice, where even moderate visitor stocks can translate into high T/R and socially salient losses in livability. Higher values of ω correspond to stronger, less tolerant reactions, whereas lower values represent weaker social feedbacks and higher tolerance.

Figure 3 shows that varying the social-pressure parameter ω restructures the equilibrium set via two fold (LP) bifurcations and a branch point (BP), yielding three distinct stable regimes, labelled across panels as branches **1**–**3**. Because this labelling is consistent in the R, T, E, and C projections, each branch can be interpreted as a coherent socio-ecological regime by jointly reading the corresponding state values across panels.

Branch 1: resident-dominated, low-tourism regime. For low to intermediate ω, the system admits a stable equilibrium with a large resident population (branch **1** in the R panel). Along this branch, R decreases only mildly as ω increases, while tourism remains low (branch **1** in the T panel). The mechanism is visible by cross-reading the panels: high R sustains capital through the resident inflow σR in eq. (4), but it also keeps environmental quality low (branch **1** in the E panel) because eq. (3) includes the direct pressure term $-\theta R$ and an additional pressure mediated by higher capital $-\beta C$. This mechanism depends on how strongly residents and tourists degrade environmental quality, i.e. on the pressure coefficients γ and θ in eq. (3) (and, indirectly, on capital-related pressure β). Varying these parameters would reshape the equilibrium levels of E and shifts the location and even the existence of the tipping points in ω. Exploring these parameters through dedicated bifurcation or sensitivity analyses could be a natural extension to this work (see illustrative example in figures 8 and 9 and baseline values in Table 1 in the Appendix).

As ω increases further, branch **1** terminates at the upper fold (LP) bifurcation (near $\omega \simeq 6.8$ in the baseline continuation). At an LP, a stable and an unstable equilibrium collide and annihilate; beyond this threshold, the resident-rich equilibrium ceases to exist. The system is therefore forced to jump discontinuously to the only remaining stable regime at that ω, namely branch **2**. This is the catastrophic transition in figure 3: residents collapse to $R = 0$, environmental quality jumps upward, and the economy reorganises into a tourism-led configuration with lower capital than on branch **1**. In this theoretical setting, the model therefore admits the possibility of a rapid depopulation event: for this parametrisation, once the social-pressure threshold is crossed the dynamics leave the resident-rich equilibrium and move abruptly to the resident-free regime, implying a fast resident outflow rather than a gradual adjustment.

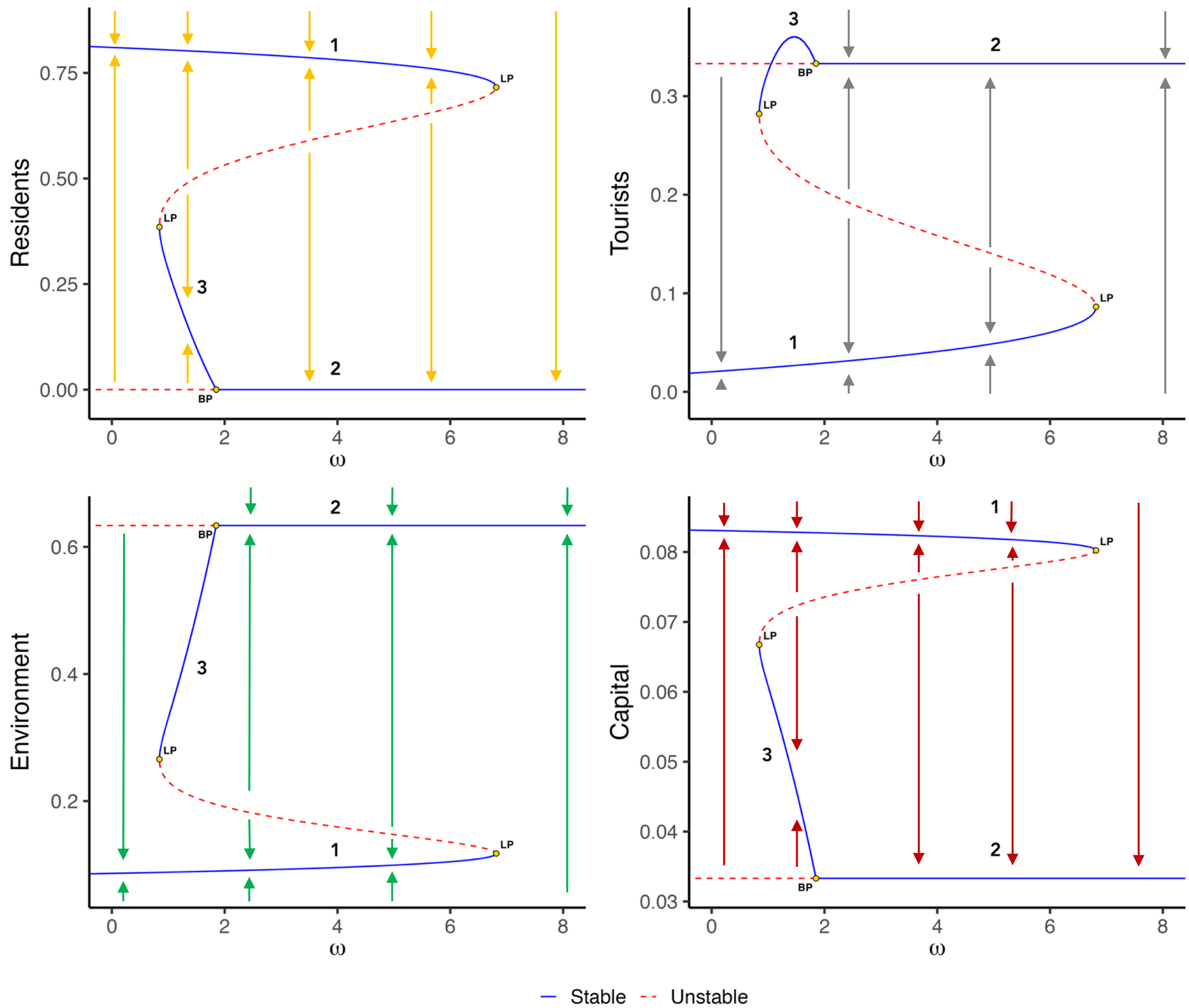

Figure 3: One-parameter bifurcation diagrams with respect to the social-pressure parameter ω. Each panel shows the projection of equilibrium branches onto one state variable (R, T, E, C). Solid blue curves denote locally asymptotically stable equilibria, while dashed red curves denote unstable equilibria. Labels 1-3 identify the stable branches to facilitate cross-reading across panels. Markers indicate special points detected by continuation: LP denotes fold (limit point) bifurcations and BP denotes a branch point. Vertical arrows indicate the local direction of the dynamics for a given ω.

Branch 2: resident-free, tourism-led regime. For sufficiently large ω, a stable regime exists with $R = 0$, high environmental quality, and substantially higher tourist levels (branch **2** in the E and T panels). Intuitively, removing the resident pressure $-\theta R$ relaxes environmental degradation and allows E to recover, which in turn raises tourist attractiveness through the $\mu_{ET}\, E/(E + \phi_{ET})$ channel in eq. (2). In this regime, capital remains strictly positive but markedly lower than on branch **1** (branch **2** in the C panel) because the resident contribution σR vanishes and the balance in eq. (4) is sustained only by tourism inflow εT against depreciation. This result depends on the relative strength of the two capital inflows, εT versus σR: when resident-based contribution is important, losing R lowers C, whereas in a tourism-driven economy (large ε relative to σ), the resident-free regime can sustain comparable or even higher capital levels. We explore this parameter dependence later.

Branch 3: coexistence regime and its non-monotone tourism response. For intermediate social pressure (approximately between the lower LP near $\omega \simeq 0.9$ and the BP near $\omega \simeq 2$ in the baseline continuation), a stable equilibrium exists in which residents and tourists coexist (branch **3**). Moving along this branch as ω increases, residents decline continuously, and eventually approach the resident-free state as a consequence of the intensity-driven social pressure $-\omega\,\mathfrak{S}(T/R)$ (i.e., excessive tourism intensity). This decline relaxes environmental pressure, so E rises sharply. Tourism is non-monotone along branch **3** because two effects compete: environmental recovery and lower congestion raise attractiveness, while declining residents weaken the resident-based "authenticity" term $\mu_{RT}\,R/(R+\phi_{RT}T+\phi_{RT})$ in eq. (2). This competition produces the hump-shaped $T(\omega)$ profile visible on branch **3**. The magnitude of this peak-and-decline pattern depends on the relative strength of congestion costs and of the environmental and authenticity attractiveness channels, as controlled by the corresponding parameters in eq. (2).

Bistability windows and tipping points interpretations. The baseline continuation shows two distinct bistability windows: (i) for ω between the lower LP and the BP, branches **1** and **3** are both stable (two resident-present equilibria separated by an unstable branch); (ii) for ω between the BP and the upper LP (near $\omega \simeq 6.8$), branches **1** and **2** are both stable (a resident-rich equilibrium coexisting with a resident-free, tourism-led equilibrium). In both cases, small exogenous shocks to one or more state variables can make the system jump from one stable regime to the other at fixed ω. For instance, a sudden drop in capital can be visualised as a vertical displacement in the bifurcation diagram, potentially moving the state across the separatrix associated with the unstable branch and into the basin of attraction of the alternative equilibrium. This creates a *resilience* issue in the dynamical sense: if the stable branches are close in state space, relatively small perturbations may be sufficient to trigger a switch, and the system will not return to the pre-shock conditions even though the original equilibrium remains locally stable.

By contrast, slow drifts in ω can carry the system to an LP and trigger an abrupt regime shift; this is a matter of structural *robustness*, because at a fold the equilibrium set itself is reorganised (a stable and an unstable equilibrium collide and a branch vanishes). The two LPs therefore imply *hysteresis*: after the system tips at one fold, bringing ω back to its pre-tipping value does not restore the previous regime, because that equilibrium is no longer reachable from the current branch. Recovery requires pushing ω past the second fold, where the alternative branch reappears and becomes attracting again. In practical terms, once the dynamics have jumped, for example, to the resident-free, tourism-led configuration, restoring a resident-rich state demands a much larger reduction in social pressure than the initial increase that caused the collapse, yielding a pronounced path dependence and an effectively irreversible interval of ω.

Combined effects of policies To assess whether the regime structure identified in figure 3 is robust to changes in the strength of the economic reinforcement loop, we next vary ε, the tourism-to-capital reinvestment parameter. This isolates how institutions and policies that govern the conversion of tourist expenditure into effective maintenance and investment reshape not only equilibrium levels, but also the type of long-run dynamics supported by the system. Increasing ε also progressively shifts the economy toward a tourism-driven configuration, i.e., a stylised form of *tourism monoculture* in which capital accumulation becomes increasingly sustained by the tourism inflow εT rather than by resident-based activity σR, potentially altering both the viability and the attractiveness of resident-free regimes.

Figure 4 shows how the ω-continuation changes as ε is varied. For reinvestment levels that are lower than the baseline (or absent altogether) ($\varepsilon = 0$ and $\varepsilon = 0.01$), the qualitative organisation of equilibria remains essentially unchanged relative to the baseline: the same fold (LP) and branch (BP) bifurcations delimit resident-present and resident-free regimes, while the equilibrium values of (R, T, E, C) shift mainly in magnitude.

A qualitatively new feature emerges when reinvestment is strong ($\varepsilon = 0.15$). In this case, the capital component is visibly reshaped and lifted: C no longer collapses along the resident-free branch, and the resident-present equilibrium supports substantially higher capital levels because the inflow εT can partly compensate for the loss of the resident contribution σR (a plausible marker of tourism monoculture). Importantly, this configuration also provides a stylised signature of overtourism in regime terms: high tourist levels and high capital can coexist with a strongly depleted local population ($R \approx 0$). In the long-run equilibria traced here (i.e., not in transients), the environmental outcome is partly rebalanced by resident disappearance: under the baseline parametrisation, resident and tourist pressures enter with comparable strength, so the drop of the resident load offsets part of the tourism-driven impact, allowing E to stabilise at levels that would otherwise be unattainable under simultaneously high T and high R. Moreover, we detect a Hopf bifurcation (H) on the resident-present equilibrium branch: as ω increases, the equilibrium loses local asymptotic

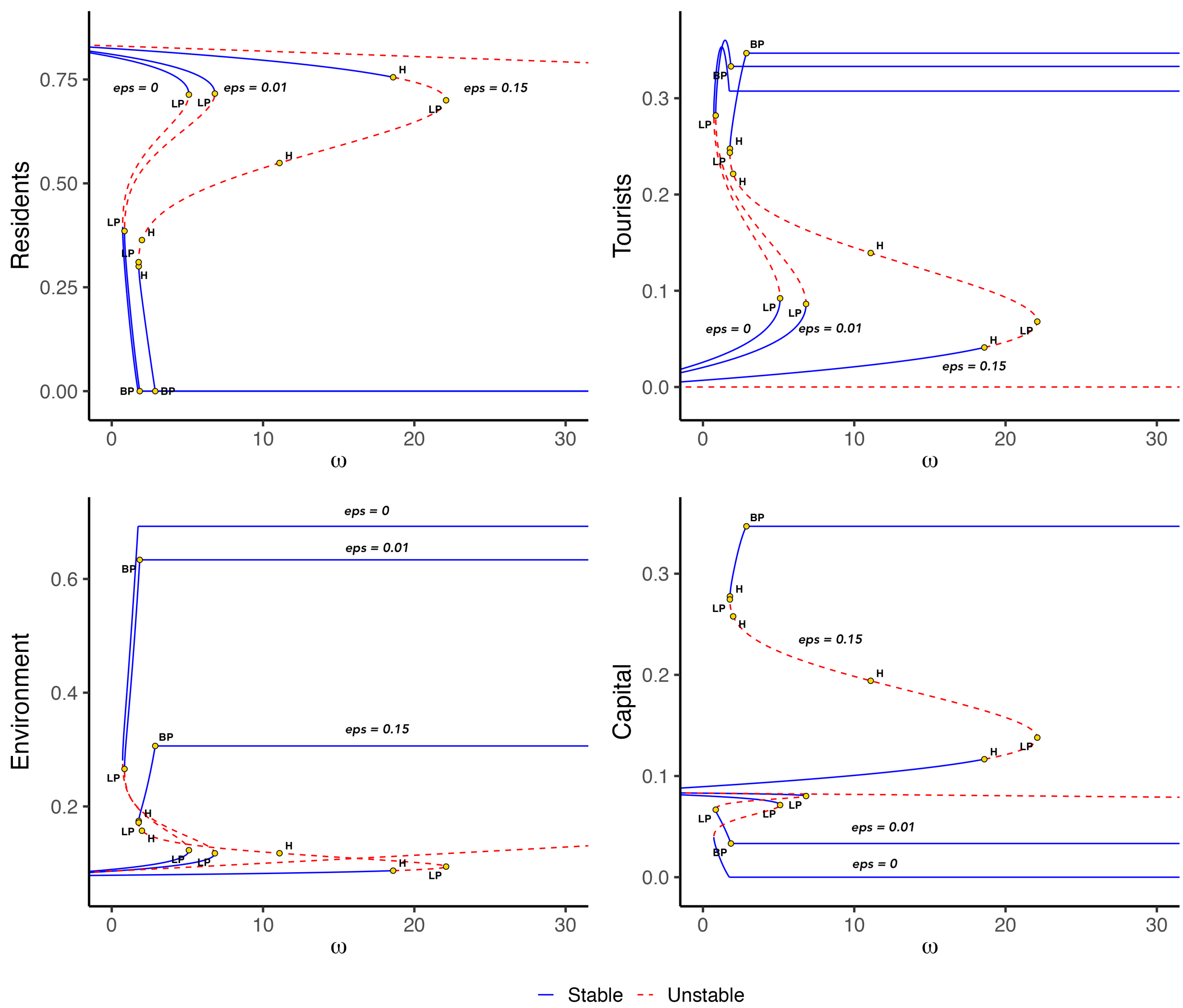

Figure 4: One–parameter bifurcation diagrams with respect to ω for different values of ε. Larger reinvestment from tourism ($\varepsilon = 0.15$) induces a Hopf bifurcation, giving rise to oscillatory dynamics.

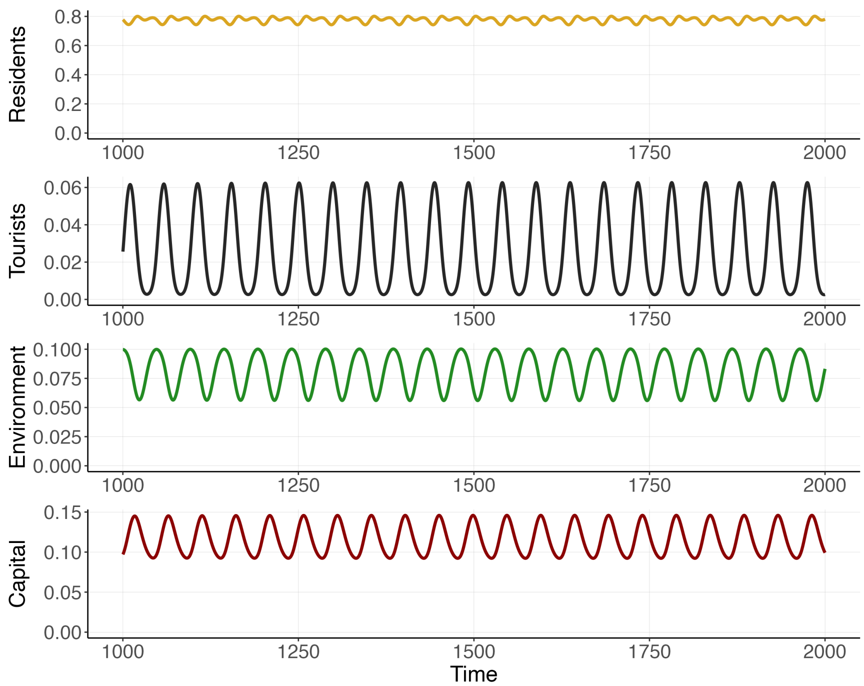

Figure 5: Time series of the four state variables in the oscillatory regime beyond the Hopf bifurcation.

stability, and a stable oscillatory regime becomes possible. Mechanistically, increasing ε strengthens the positive feedback loop $T \to C \to T$, because (i) capital accumulation responds more strongly to tourism through $\partial \dot{C}/\partial T = \varepsilon$ in eq. (4), and (ii) tourist attractiveness increases with capital through the saturating term $\mu_{CT}\, C/(C + \phi_{CT}(T + R) + \phi_{CT})$ in eq. (2). When this reinforcement is sufficiently strong, and social pressure ω tightens the resident constraint, the coupled adjustment of (T, C) can overshoot and destabilise the fixed point, producing recurrent boom-bust dynamics rather than convergence (cf. the time-domain behaviour in figure 5).

From an overtourism perspective, this matters because it shows that destabilisation does not require a shift to a resident-free equilibrium: the same feedback architecture can instead generate persistent cycles in which phases of high visitation and capital accumulation alternate with phases of ecological stress and partial recovery. In other words, overtourism is not only associated with equilibrium collapse or bistability windows, but can also manifest as an intrinsically dynamical regime driven by a strong tourism-investment reinforcement under high social pressure.

Figure 6 maps the bifurcation structure of the system in the two-parameter space (ω, ε) (analysis ongoing: current map is based on a partial exploration of the parameter plane). The fold and stability-loss transitions identified in the one-parameter continuations (figure 4) appear here as parts of an organised codimension-two geometry. In particular, the diagonal curve is the limit point locus (LP): it is the two-parameter continuation of the limit point found in the one-parameter scans and it separates the coexistence branch from the residents-collapse branch. Along this LP curve two equilibria collide and are created/annihilated; at its endpoint, the fold locus terminates at a Bogdanov-Takens (BT) point, where the limit point and Hopf bifurcation curves meet, capturing the onset of oscillatory dynamics in the neighbourhood of a fold. A generalized Hopf (GH) point further marks a change in the criticality of the Hopf bifurcation, implying a switch in the stability properties of the emerging periodic orbits. Together, these codimension-two singularities partition the (ω, ε) plane into regions associated with qualitatively distinct long-run behaviours and delineate the parameter domain where incremental shifts translate into abrupt qualitative reorganisation of long-run outcomes.

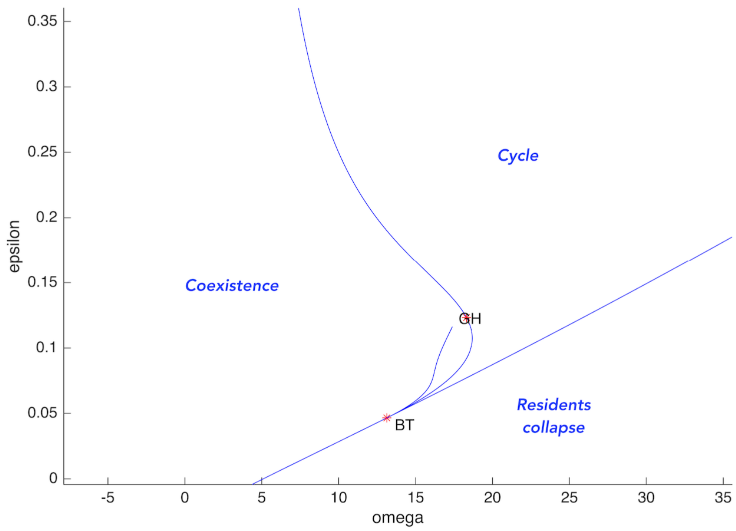

Figure 6: Two-parameter bifurcation diagram in the (ω, ε) plane. Curves show the loci of limit point (LP, fold) and Hopf (H) bifurcations; BT and GH indicate codimension-two organising points. (Partial map: only a portion of the bifurcation set is shown.)

4 Conclusions

In this work we revisited tourism carrying capacity by returning to its original logic as a constraint emerging from system dynamics, while explicitly incorporating the reasons why many contemporary conceptualizations remain partial. In our formulation, capacity is not a single, externally imposed number. It is multidimensional and state-dependent: it shifts with the joint socio-ecological configuration, and it can be studied as an endogenous feature implied by the same feedback structure that governs residents, tourists, the environment, and the economic base. This reframing provides a coherent bridge between the intuitive appeal of "capacity" and the modern understanding that tourism systems are coupled, nonlinear, and shaped by interacting mechanisms rather than by limiting one factor.

A key implication is that carrying capacity, even when defined carefully and computed with sophisticated methods, can be conceptually insufficient if it is treated as a decision target or as a direct instrument of sustainability. In our framework, carrying capacity emerges as an instantaneous growth constraint: it identifies the state-contingent condition under which the tourist stock ceases to expand given the contemporaneous levels of residents, environmental quality, and capital. That condition, however, is not equivalent to a sustainable configuration. Reaching a nominally "optimal" capacity can alter the conditions of the other subsystems, with no guarantee that residents persist, environmental quality remains acceptable, or capital evolves in a desirable direction. More fundamentally, in nonlinear systems the same level of tourism can be associated with qualitatively different long run outcomes depending on where the system starts and how it is approached. Multistability, hysteresis, and abrupt transitions imply that identical tourism levels may sit in different basins of attraction, so that policy choices calibrated around a single threshold can yield sharply different outcomes when the system is close to regime boundaries or when slow parameter changes push it across them. This does not eliminate the practical usefulness of operational thresholds, but it changes their meaning: thresholds are not "the" carrying capacity, and they cannot be used as a standalone proxy for sustainability.

This perspective also clarifies why long standing framing questions in the field are incomplete unless embedded in a dynamical, state space view. The classical "How many is too many?" focus, and the later shift toward "How much change from natural conditions is acceptable given the goals and objectives of an area?" both reflect legitimate management concerns, but both risk compressing a multidimensional, feedback driven process into a one dimensional control narrative. Our results suggest a more general interpretation: what matters is the evolving socio-ecological state as a whole and the mechanisms that generate its regimes. Tourism pressure cannot be evaluated independently of the resident base, environmental conditions, and the economic and infrastructural system that co evolves with tourism itself, because these variables do not merely respond to tourism, they jointly define what tourism "means" in the system at any given time. In this sense, the object of governance is not a scalar capacity, but a coupled configuration whose quantitative state determines the qualitative regime it belongs to.

Methodologically, the minimal model shows why this state dependent view is not only conceptually appealing but formally necessary. Even with a deliberately simple set of mechanisms, the coupled dynamics generate a structured regime landscape, including alternative stable equilibria and, depending on parameter combinations, persistent endogenous fluctuations. This expands the usual picture of overtourism outcomes beyond steady state collapse or replacement by a single degraded equilibrium. The same feedback architecture can produce recurrent phases of crowding, environmental stress, partial recovery, and renewed pressure, implying that overtourism like conditions may also manifest as self sustained cycles rather than as a one way transition. A regime perspective therefore becomes essential: the relevant policy question is not solely how to keep tourism below a number, but how to keep the system away from high risk regions of its regime map and how to maintain sufficient margins of stability as social, economic and environmental conditions fluctuate.

This points to a practical next step: identifying "desirable" regime regions together with stakeholders, negotiating the relevant trade-offs explicitly, and then translating these objectives into a monitored set of indicators that anchors deliberation and accountability. In this setting, models do not deliver a single number to enforce; they provide a mechanism-based link between interventions and indicator trajectories, quantifying trade-offs and allowing policy packages to be evaluated in terms of system-level performance, including their robustness to slow drifts in social and economic conditions and their resilience under disturbances.

These implications are particularly salient for heritage cities that face touristification dynamics. In our stylized representation, once social intensity mechanisms push the system past critical boundaries, a resident free regime can become the attracting outcome, consistent with a drift toward a museum like configuration. Conversely, interventions that reduce effective social pressure can, in principle, restore resident persistence when the system lies within coexistence ranges, because crossing back into that region reinstates a resident present attracting regime. Importantly, however, such changes cannot be treated as single lever fixes. Restoring one dimension without coordinating the others can reactivate degradation pathways, for instance when resident recovery and the associated capital base amplify environmental pressures. The model therefore supports a policy interpretation that is simultaneously state aware and mechanism aware: effective governance requires coordinated and adaptive strategies that act on multiple subsystems.

Our contribution is therefore best read as a repositioning of carrying capacity. We do not propose abandoning it, but clarifying what it can and cannot do. Capacity is informative as an endogenous, state contingent descriptor of constraints within the tourism subsystem, and as a lens to interpret where and why growth pressures reverse. It is not, by itself, a sustainability criterion, nor a reliable policy target in the presence of nonlinear feedbacks, multiple attractors, and regime shifts. A governance strategy that relies primarily on identifying a single "best" capacity value is structurally fragile when the system is path dependent and when policy levers interact across subsystems.

At the same time, the present analysis has clear limitations. The model is intentionally qualitative and stylized: it is designed to expose mechanisms and regime structure, not to provide case specific quantitative prescriptions. We do not undertake an empirical calibration, we do not aim to reproduce observed trajectories, and we do not focus on transient dynamics as a policy object in itself. In particular, the work emphasizes long run regimes and their organizing transitions rather than short term management under transient fluctuations. We also do not address classes of tipping behavior that require explicit modelling of exogenous shocks, rapid parameter shifts, or rate dependent transitions, which may be central in real policy contexts. These limitations are not incidental: they reflect the choice to use a minimal framework to clarify why threshold based reasoning can fail even before case specificity and operational complexity are introduced.

These considerations also suggest directions for policy-oriented extensions. A natural next step is to expand the regime mapping across additional control dimensions aligned with canonical tourism dynamics parameters, and to systematically explore how different levers reshape the regime landscape, including the boundaries that separate coexistence, tourist dominated, and fluctuating regimes. More importantly, translating the present insights into decision support requires moving from a minimal model to higher fidelity representations that retain the mechanism aware, state dependent logic while incorporating richer sectoral detail, observable indicators, and explicit policy instruments. This suggests the development of calibrated, data linked models and digital twin style frameworks in which the interacting dimensions highlighted here are represented with sufficient realism to evaluate concrete interventions, stress test strategies under uncertainty, and assess robustness and resilience across stakeholder defined objectives. In that setting, the contribution of carrying capacity would be integrated into a wider decision architecture: not as a single number to be imposed, but as part of a model based, participatory process that evaluates sustainability within the full complexity of the coupled socio-ecological system.

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Author contributions statement

SR and MB designed the model, and contributed to the interpretation of the results. SR implemented the model, conducted numerical experiments. SR, MB and CG contributed to result interpretation and discussion.
All authors contributed equally to manuscript writing, critically reviewed the findings, and approved the final version.

Competing Interests

The authors declare that they have no competing financial or non-financial interests that could have appeared to influence the work reported in this paper.

Data Availability

All codes and datasets used in this study are provided in the *Supplementary Information* or are available upon reasonable request.

A Benefit–disutility decomposition

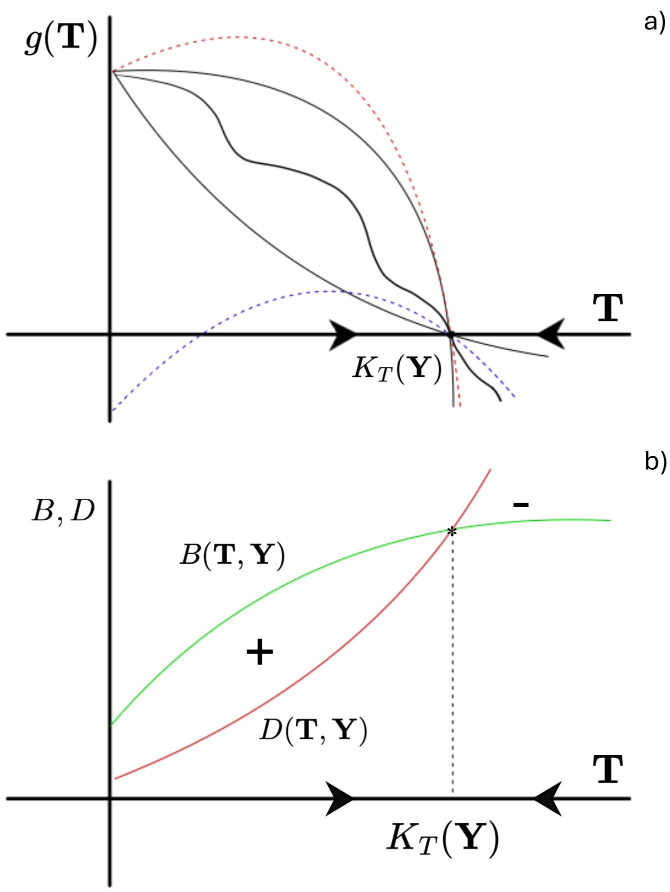


Figure 7: Existence and uniqueness of the tourism carrying capacity. (a) Illustrative shapes of the per-capita tourist growth function $g(T)$ (for fixed socio-ecological conditions Y). Solid black curves satisfy Assumptions 1–2, and therefore admit a unique positive root K_T (shown at the same location for all curves for comparison), which is locally asymptotically stable. The dashed blue curve violates $g(0) > 0$ yet still has two positive equilibria, one stable and one unstable, so a carrying-capacity-like stable level can still exist. The dashed red curve violates global monotonicity but crosses zero only once, and thus still yields a unique K_T. Arrows indicate the direction of the dynamics: T increases where $g(T) > 0$ and decreases where $g(T) < 0$. (b) Benefit-disutility representation: tourism grows when benefits exceed disutilities ($B > D$) and declines otherwise. Under Assumptions 1–2, B crosses D only once, implying a unique carrying capacity.

Here we discuss the generality of Assumptions 1–2. First, they are stated as *sufficient* conditions for existence and uniqueness of $K_T(\mathbf{Y})$, but they are not *necessary* in full generality. This is useful, because it clarifies that a well-defined carrying capacity can arise even in cases where these assumptions, already stated in a very permissive form, do not hold. For example, concerning Assumption 1, a positive root of $g(\mathbf{T}) = 0$ may exist even without a global sign change. For instance, $g(\mathbf{T}) = (\mathbf{T} - 1)^2$ is nonnegative for all $\mathbf{T}$ and still has a strictly positive root at $\mathbf{T} = 1$, yet g never becomes negative. However, since we ask for $K_T(\mathbf{Y})$ being a real *carrying capacity*, as an attracting point for the tourist dynamics, then a *local* sign change around the root is necessary: $g(\mathbf{T})$ must be positive just below $K_T(\mathbf{Y})$ and negative just above it, so that $\mathbf{T}(t)$ is pushed toward $K_T(\mathbf{Y})$ from both sides (see figure 7a)). In that sense, the sign-change requirement is not necessary for the mere existence of a root, but it captures the qualitative condition needed for $K_T(\mathbf{Y})$ to act as an attractor. Moreover, the requirement $g(0) > 0$ is not necessary for the existence of a positive attracting level. In particular, a positive root may exist even if $g(0) \leq 0$ (blue dashed line in figure 7a)): g can be negative at very low visitation, become positive at intermediate levels and then turn negative again (an Allee-type pattern), still producing a positive attracting equilibrium (note: not necessarily unique!).

Concerning Assumption 2, uniqueness does not necessarily require global monotonicity. The function g may be locally non-monotone (see dashed red curve in figure 7a)) yet still cross zero exactly once and remain negative thereafter, yielding a unique positive solution to eq. (10). Assumption 2 is therefore a convenient sufficient condition that rules out multiple crossings by construction, but the uniqueness conclusion can hold under weaker shape restrictions on g.

Despite these logical exceptions, the scenarios that violate 1–2 are essentially pathological for tourism systems. With attractiveness benefits that saturate in $\mathbf{T}$ and congestion disutilities that intensify with visitation, $g(\mathbf{T})$ is expected to start positive at low $\mathbf{T}$, decrease with $\mathbf{T}$, and become negative for sufficiently large $\mathbf{T}$, making 1–2 both empirically plausible and broadly applicable.

To make this argument more transparent, it is useful to rewrite the per-capita rate g as a reduced-form balance between reinforcing components of destination attractiveness and countervailing forces such as congestion and competition with other destinations,

$$g(\mathbf{T}, \mathbf{Y}) = B(\mathbf{T}, \mathbf{Y}) - D(\mathbf{T}, \mathbf{Y}), \tag{15}$$

where B aggregates attractiveness benefits (e.g. environmental quality, capital and services, resident-based authenticity) and D aggregates disutilities and outside-option costs (e.g. crowding, limited service capacity, competitiveness relative to alternative destinations). The split in eq. (15) is deliberately general: it does not commit to specific functional forms and allows both B and D to depend on visitation $\mathbf{T}$ and on the broader socio-ecological state $\mathbf{Y}$.

We can now restate Assumptions 1–2 in terms of the benefit and disutility components B and D, which makes their economic content explicit. For a fixed socio-ecological state $\mathbf{Y}$, Assumption 1 (sign change) can be read as requiring positive net attractiveness at low visitation and negative net attractiveness at some higher level:

$$g(0, \mathbf{Y}) = B(0, \mathbf{Y}) - D(0, \mathbf{Y}) > 0, \qquad \exists\, \tilde{\mathbf{T}} > 0 : \; B(\tilde{\mathbf{T}}, \mathbf{Y}) - D(\tilde{\mathbf{T}}, \mathbf{Y}) < 0. \tag{16}$$

The first inequality states that, when visitation is negligible, perceived benefits exceed disutilities and the destination attracts tourists. The second inequality states that, at sufficiently high visitation, disutilities can outweigh benefits, so that net tourist growth becomes negative and an interior equilibrium becomes possible (see figure 7b)).

Assumption 2 (strict monotonicity) becomes a marginal condition: for all $\mathbf{T} > 0$,

$$\frac{\partial}{\partial \mathbf{T}} \Big[B(\mathbf{T}, \mathbf{Y}) - D(\mathbf{T}, \mathbf{Y}) \Big] < 0, \qquad \text{equivalently} \qquad \frac{\partial B}{\partial \mathbf{T}} < \frac{\partial D}{\partial \mathbf{T}}. \tag{17}$$

This inequality formalises the idea that marginal benefits of additional visitation do not increase faster than marginal disutilities: attractiveness components typically saturate (so $\partial B / \partial \mathbf{T}$ is small or negative), whereas congestion and related costs intensify (so $\partial D / \partial \mathbf{T}$ is positive and sufficiently large).

B Existence and uniqueness in SES formulation

For given socio-ecological conditions $\mathbf{Y} = (\mathbf{R}, \mathbf{C}, \mathbf{E})$, the tourist subsystem in eq. (2) can be written in the general attractiveness form eq. (9) as

$$\dot{\mathbf{T}} = \mathbf{T}\, g(\mathbf{T} \mid \mathbf{R}, \mathbf{C}, \mathbf{E}), \tag{18}$$

with per-capita net growth rate

$$g(\mathbf{T} | \mathbf{R}, \mathbf{C}, \mathbf{E}) = \overbrace{\mu_{CT} \frac{\mathbf{C}}{\mathbf{C} + \phi_{CT}(\mathbf{T} + \mathbf{R}) + \phi_{CT}}}^{\text{Economic}} + \overbrace{\mu_{ET} \frac{\mathbf{E}}{\mathbf{E} + \phi_{ET}}}^{\text{Environmental}} + \overbrace{\mu_{RT} \frac{\mathbf{R}}{\mathbf{R} + \phi_{RT}\mathbf{T} + \phi_{RT}}}^{\text{Social}} - a - \overbrace{\alpha_T (\mathbf{T} + \mathbf{R})}^{\text{Infrastructural}} \tag{19}$$

For any fixed $(\mathbf{R}, \mathbf{C}, \mathbf{E})$, the function $g(\cdot \mid \mathbf{R}, \mathbf{C}, \mathbf{E})$ is continuous on $[0, \infty)$ and differentiable on $(0, \infty)$. Moreover, it is strictly decreasing in $\mathbf{T}$, because

$$\frac{\partial}{\partial \mathbf{T}}\left(\mu_{CT}\,\frac{\mathbf{C}}{\mathbf{C}+\phi_{CT}(\mathbf{T}+\mathbf{R})+\phi_{CT}}\right) = -\mu_{CT}\,\frac{\mathbf{C}\phi_{CT}}{\left(\mathbf{C}+\phi_{CT}(\mathbf{T}+\mathbf{R})+\phi_{CT}\right)^2} < 0,$$

$$\frac{\partial}{\partial \mathbf{T}}\left(\mu_{RT}\,\frac{\mathbf{R}}{\mathbf{R}+\phi_{RT}\mathbf{T}+\phi_{RT}}\right) = -\mu_{RT}\,\frac{\mathbf{R}\phi_{RT}}{\left(\mathbf{R}+\phi_{RT}\mathbf{T}+\phi_{RT}\right)^2} < 0,$$

$$\frac{\partial}{\partial \mathbf{T}}[-\alpha_T(\mathbf{T}+\mathbf{R})] = -\alpha_T < 0,$$

while the environmental term is independent of $\mathbf{T}$. Hence $\partial g/\partial \mathbf{T} < 0$ for all $\mathbf{T} > 0$, which matches the strict-monotonicity condition in Assumption 2.

Assumption 1 is satisfied whenever net attractiveness is positive at negligible visitation,

$$g(0 \mid \mathbf{R}, \mathbf{C}, \mathbf{E}) = \mu_{CT}\,\frac{\mathbf{C}}{\mathbf{C}+\phi_{CT}\mathbf{R}+\phi_{CT}} + \mu_{ET}\,\frac{\mathbf{E}}{\mathbf{E}+\phi_{ET}} + \mu_{RT}\,\frac{\mathbf{R}}{\mathbf{R}+\phi_{RT}} - \alpha_T\mathbf{R} - a > 0,$$

and it necessarily becomes negative for sufficiently large $\mathbf{T}$ because the linear congestion term $-\alpha_T\mathbf{T}$ dominates while the benefit terms are bounded (the capital and authenticity terms vanish as $\mathbf{T} \to \infty$). Therefore, by Proposition 1, there exists a unique state-dependent tourism carrying capacity $K_T(\mathbf{R}, \mathbf{C}, \mathbf{E}) > 0$ implicitly defined by

$$g(K_T(\mathbf{R}, \mathbf{C}, \mathbf{E}) \mid \mathbf{R}, \mathbf{C}, \mathbf{E}) = 0. \tag{20}$$

Because eq. (20) is defined pointwise in the state space, K_T moves with the evolving socio-ecological conditions and captures, in a single object, how the economic, environmental, social, and congestion channels jointly constrain feasible visitation. The tourism carrying capacity $K_T(\mathbf{Y})$ can be computed numerically as the unique positive root of the implicit equation $g(T \mid \mathbf{Y}) = 0$ (e.g. by bisection or Newton methods), whose existence and uniqueness are ensured by Assumptions 1–2. Along a trajectory $\mathbf{Y}(t)$, this yields a time-varying capacity $K_T(t) := K_T(\mathbf{Y}(t))$ obtained by solving the same root-finding problem pointwise in time.

C More on policy interactions

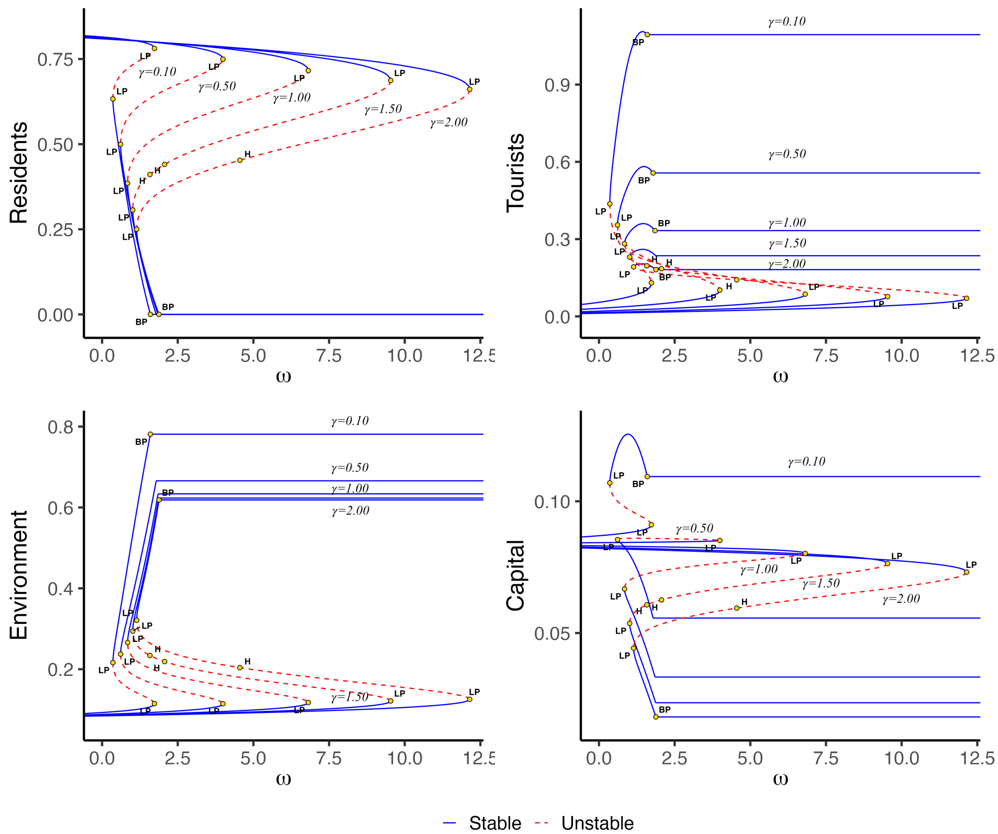
Figures 8 and 9 summarise how the one-parameter regime map in ω changes as the environmental impact of tourists (γ) and residents (θ) is varied. When environmental impacts are mild (small γ and/or θ), the continuation in ω is essentially single-branched: at $\omega = 0$ the system settles into a unique, locally stable coexistence equilibrium with high R, high E, and positive C sustained by the combined inflows $\sigma R + \varepsilon T$. In this low-impact setting, increasing ω mainly induces a smooth reallocation of the equilibrium levels (a gradual decline in R and a corresponding adjustment in T, E, and C), without fold-induced tipping or hysteresis.

As environmental impacts strengthen (larger γ or θ), the equilibrium branch bends and a pair of limit points (LP) appears, opening a bistable interval in ω where two alternative stable equilibria coexist: a resident-present coexistence state and a resident-poor, tourism-led state. In this regime, the LP points act as tipping thresholds: small parameter shifts can trigger abrupt transitions, and the reverse transition occurs at a different ω value, implying hysteresis.

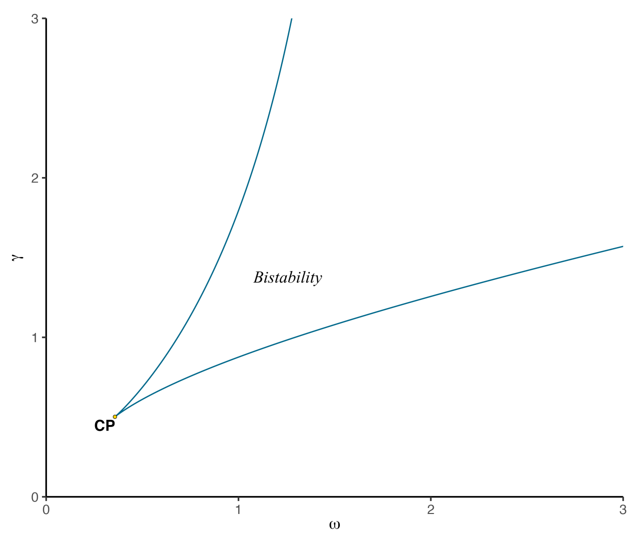
The lower panels (b) display the corresponding two–parameter continuations in the (ω, γ) and (ω, θ) planes, directly linking to the one–dimensional diagrams above. Each curve traces the loci of limit point bifurcations that delimit the bistability regions observed in panels (a). The cusp point (CP) marks the boundary beyond which bistability disappears, indicating a qualitative reorganization of the equilibrium landscape.

One can exit the bistable region by either increasing ω past $\omega_{\max}$ or decreasing it below $\omega_{\min}$. When both environmental stress (γ or θ) and ω are large, the system lies deeper inside the wedge and larger parameter changes are required to cross a fold. At low environmental stress (near the CP cusp point), the wedge collapses and bistability disappears—consistent with the one–parameter sections above.

A salient asymmetry emerges when comparing the two planes. The (ω, γ) wedge is wider and extends over a broader range of ω than the (ω, θ) wedge. Equivalently, for comparable ω, the bistable interval in γ

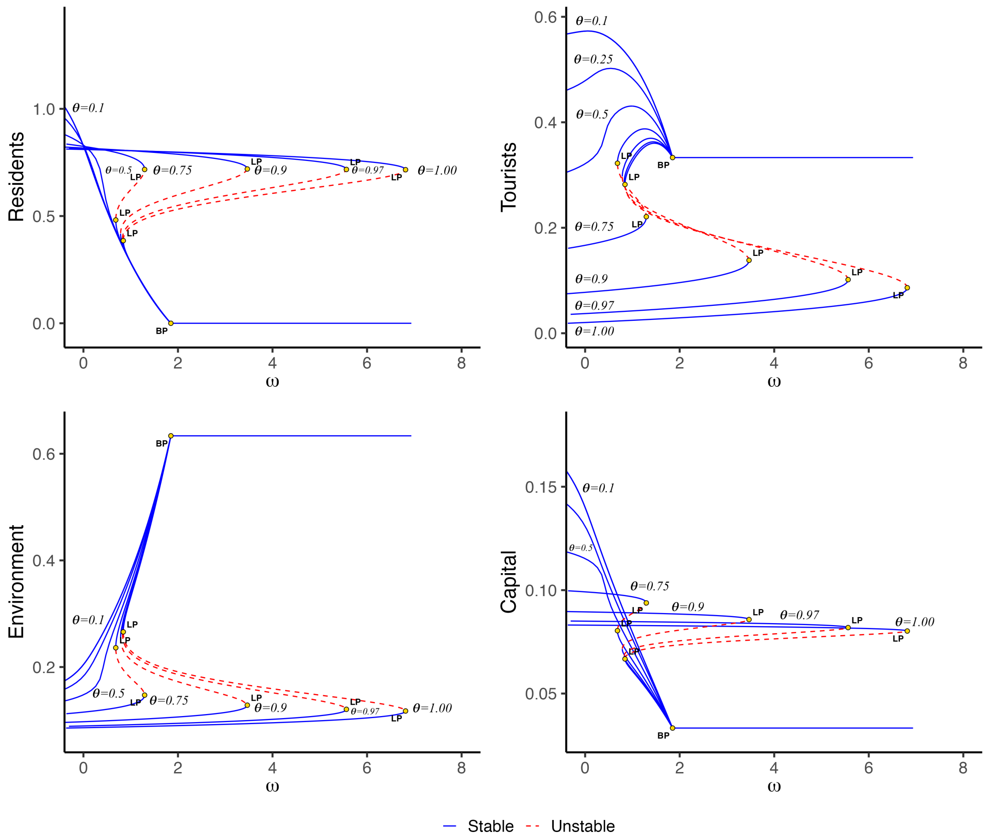


(a) One-parameter continuation in ω for different values of γ.

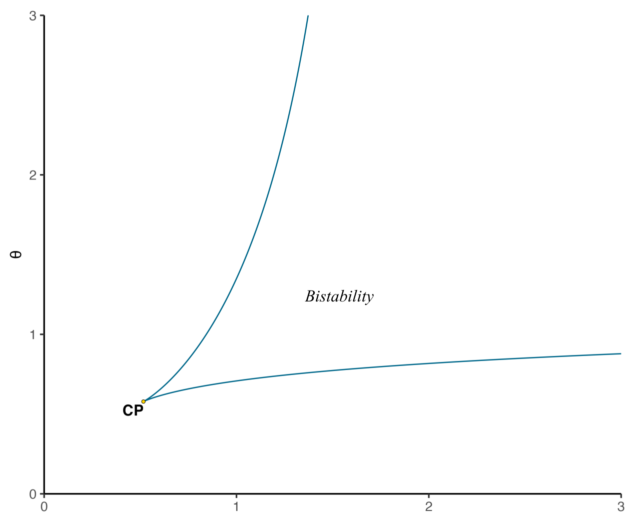


(b) Two-parameter continuation in the (ω, γ) plane.

Figure 8: **Bifurcation structure with social tolerance (ω) and tourist-induced environmental pressure (γ).** Top: codimension-one continuations in ω for different γ. Stable equilibria are shown in blue and unstable ones in dashed red. Bottom: codimension-two continuation in the (ω, γ) plane showing the loci of limit point bifurcations delimiting the bistability region.



(a) One-parameter continuation in ω for different values of θ.



(b) Two-parameter continuation in the (ω, θ) plane.

Figure 9: **Bifurcation structure with social tolerance** (ω) **and resident-induced environmental pressure** (θ)**.** Top: codimension-one continuations in ω for different θ. Stable equilibria are shown in blue and unstable ones in dashed red. Bottom: codimension-two continuation in the (ω, θ) plane showing the loci of limit point bifurcations delimiting the bistability region.

is larger than in θ; and for comparable environmental stress, $\omega_{\max}(\gamma)$ tends to be higher than $\omega_{\max}(\theta)$. This indicates a stronger coupling between social sensitivity and *tourist–induced* environmental pressure (γ) than with *resident–induced* pressure (θ): mitigating γ shrinks the bistability wedge more effectively than equal reductions in θ, while lowering ω shifts *both* frontiers, enlarging the monostable domain.

D Baseline parameters

Parameter	Meaning	Value
Residents		
μ_{ER}	Environmental benefit weight	5
μ_{CR}	Capital benefit weight	10
ϕ_{ER}	Environmental half-saturation	1
ϕ_{CR}	Capital half-saturation	1
ω	Intensity-pressure strength	1
s	Logistic steepness	10
m	Logistic inflection point	0.5
α_R	Density cost for residents	1
o	Exogenous demographic drift	0
Tourists		
μ_{ET}	Environmental attractiveness weight	10
μ_{CT}	Capital attractiveness weight	10
μ_{RT}	Authenticity weight	5
ϕ_{ET}	Environmental half-saturation	0.5
ϕ_{CT}	Capital half-saturation	1
ϕ_{RT}	Authenticity attenuation scale	0.5
α_T	Density disutility for tourists	1
a	Outside-option competitiveness	6
Environment		
r	Intrinsic regeneration rate	1
K_E	Environmental carrying capacity	1
β	Capital-induced pressure	1
γ	Tourist-induced pressure	1
θ	Resident-induced pressure	1
Capital		
δ	Depreciation rate	0.1
ε	Tourism contribution to capital	0.01
σ	Resident contribution to capital	0.07

Table 1: Baseline parameter values used for the bifurcation analysis. Cf. with [1]