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Developing a quantitative analytical framework for carbon neutrality in tourism-dependent regions

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Achieving carbon neutrality in tourism-dependent regions poses a critical challenge for global climate governance. However, existing studies lack frameworks to analyze the linkages between tourism and regional carbon neutrality. This study fills the gap by developing an interdisciplinary quantitative framework integrating Logarithmic Mean Divisia Index decomposition and system dynamics modeling. It systematically examines tourism-carbon neutrality interactions across industry, residents, land use, and Carbon Capture and Storage. Using Hainan Island (2010–2021) as a case study, the simulations reveal the following: (1) fluctuating growth in net emissions alongside declining carbon intensity; (2) the tertiary and secondary industries are the main emitters, with the former decarbonizing faster and the latter lagging behind in the green transition, while the primary industry is at a low level of both carbon emissions and carbon intensity; (3) residential emissions are driven by urbanization and living standards; (4) land-use carbon sinks decline slightly despite urban green expansion, due to construction land encroachment; (5) sensitivity analysis shows tourism growth in Hainan currently increases regional emissions but reduces carbon intensity. The novelty of this study lies in mapping dynamic relationships through a coupled approach and providing tools for destination-specific decarbonization strategies. Practical implications emphasize the need for integrated policies that balance tourism growth, industrial decarbonization, residential planning, and ecosystem restoration. By aligning economic objectives with climate resilience, this approach advances climate governance for policymakers in tourism-dependent regions.

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Introduction

The global transition from an industrialized past to a sustainable future has elevated environmental remediation to a critical international priority (Işık et al., 2024a). Sustainable development emerges as a mediating framework between anthropogenic activities and ecological preservation (Henrysson et al., 2024), integrating economic growth with multidimensional objectives spanning social equity, environmental stewardship, and transnational collaboration (Işık et al., 2024b). Operationalizing this vision, the United Nations (2022) established 17 sustainable development goals (SDGs) that provide actionable benchmarks for cultivating inclusive socioeconomic systems (Qi et al., 2024; Gallardo-Vázquez et al., 2024a).

Scholarship increasingly recognizes environmental, social, and governance (ESG) criteria as operational drivers of SDG implementation (Sinha et al., 2024; Han et al., 2024; Li et al., 2024). Given the SDGs' inherent comprehensiveness (Biermann et al., 2022), their integration with ESG metrics through unified analytical frameworks enables systematic examination of sustainability synergies (Işık et al., 2024c). Building upon the triple bottom line paradigm's emphasis on balancing social, environmental, and economic priorities (Gallardo-Vázquez et al., 2024b), recent theoretical advancements propose the ECON-ESG model. This composite framework incorporates economic dimensions into traditional ESG parameters, establishing a holistic sustainability assessment mechanism (Işık et al., 2024d; Işık et al., 2025).

The concept of sustainable tourism emerged as a direct response to broader sustainable development discourses, with scholars and policymakers coalescing around the operational definition provided by the UNWTO (2005): "tourism that takes full account of its current and future economic, social and environmental impacts, addressing the needs of visitors, the industry, the environment and host communities." This tripartite equilibrium—balancing economic viability, environmental integrity, and socio-cultural equity—has solidified as the dominant paradigm in tourism sustainability research (Mihalič, 2020; Santos-Rojo et al., 2023). As a global economic pillar contributing approximately one-tenth of global economic output and employment opportunities (Giambona et al., 2024), tourism's embeddedness within ecological systems and socio-political structures (Mihalič, 2020) positions it as a critical leverage point for advancing both ECON-ESG integration and SDG implementation (Legendre et al., 2024; Shin et al., 2025; Ye et al., 2025).

However, climate change has emerged as a critical disruptor of socioeconomic systems (Iles et al., 2024), with its transformative effects permeating global economic sectors and fundamentally challenging sustainable development trajectories (Işık et al., 2025). The tourism industry, given its climate and natural resource-dependent characteristics (Dogru et al., 2019; Li et al., 2025), faces disproportionate vulnerability to these changes, especially in tourism-dependent areas including mountains, coasts and islands (Alvarez et al., 2022; IPCC, 2022). Despite the sector's 8.8% contribution to global carbon emissions and projections indicating emission growth trajectories that conflict with decarbonization commitments (Sun et al., 2024), systemic mitigation efforts remain insufficient (Peeters et al., 2024). The carbon footprint extends beyond direct tourism activities to encompass complex value chains involving transportation, hospitality, and manufacturing sectors (Zha et al., 2020). Its profile creates dynamic interdependencies between tourism development and carbon neutrality objectives in destinations. Given the sector's dual role as both climate change contributor and victim, this urgency has become critical, demanding advanced analytical frameworks to examine the tourism-carbon neutrality nexus and design sustainable growth strategies that reconcile tourism

development with environmental imperatives (Işık et al., 2017; Işık et al., 2018; Scott & Gössling, 2022).

Current tourism research demonstrates limited investigation into the interplay between tourism development and ECON-ESG factors in shaping regional carbon neutrality outcomes. Existing scholarship, limited by researchers' theoretical lenses and methodological orientations, has primarily introduced isolated factors—including economic growth, (renewable) energy consumption, urbanization, environmental policy and green innovation—in analyzing the tourism-carbon emission nexus (Shang et al., 2023a; Erdoğan et al., 2024; Kumail et al., 2024; Zhang et al., 2024). Within the ECON-ESG framework, the interactions between tourism development and carbon neutrality determinants remain underexplored. Furthermore, existing tourism's carbon neutrality frameworks primarily employ econometric methods based on reductionism to establish causal relationships between tourism activities and emission changes (Sun et al., 2022; Segarra et al., 2024). This stems from two disciplinary limitations: tourism scholars face methodological constraints in analyzing complex systems, while mainstream researchers frequently overlook tourism-dependent regions as unique study subjects. Thus, a critical methodological gap persists: the absence of comprehensive quantitative tools for analyzing carbon neutrality in tourism-dependent regions (CNTDR) (Nepal et al., 2019; Zhou et al., 2023). This limitation impedes conceptual mapping of tourism development's mechanistic pathways influencing regional carbon neutrality and quantitative evaluation of such interactions (Craib et al., 2023; Zhang & Zhang, 2020). Addressing this knowledge gap would clarify tourism and carbon neutrality dynamics within ECON-ESG framework while establishing analytical frameworks to assess destination-specific decarbonization management strategies. As a result, this study set the following research questions (RQ):

RQ1: What mechanisms connect tourism development with regional carbon neutrality?

RQ2: How does tourism development affect regional carbon neutrality when these mechanisms are quantified?

In view of this, we innovatively combined system dynamics (SD) with the extended logarithmic mean divisia index (LMDI) method, and comprehensively established the dynamic feedback relationship between tourism development and regional carbon emissions and carbon sinks. We then developed a carbon neutrality simulation system for tourism-dependent regions, including subsystems for tourism, economy, society, carbon sinks, and carbon emissions. Using Hainan, China as a case study, we tested the validity of this framework through several tests and discussed its theoretical and practical implications.

This paper's marginal contributions include the following: first, an innovative aspect of the research approach is its disaggregation of regional carbon neutrality into four sectors—industrial economy, household consumption, land use, and carbon sink infrastructure—to reveal how tourism influences inter-sector dynamics that aggregate analyses fail to capture. Further, it develops an extended-LMDI decomposition model, systematically isolating key drivers across emission subsystems. This integrated approach improves methodological rigor in driver detection while elucidating tourism's differential impacts across constituent sectors.

Second, this research introduces the first integration of SD modeling within the CNTDR framework to conceptualize tourism development's multifaceted interactions with sectoral emission drivers, establishing feedback mechanisms. Specifically, the coupling of LMDI decomposition with causal loop diagramming identifies multiple reinforcing/balancing feedback pathways between tourism growth and carbon neutrality processes. It

advances theoretical comprehension of tourism-environment nonlinear interactions through systemic interdependency mapping while providing a new dynamic analytical perspective within sustainable tourism paradigms, with significant theoretical implications.

Third, this study pioneers a SD simulation model for tourism-dependent regions, developing a quantitative analytical tool to decipher the complex interactions between tourism development and regional carbon neutrality. It overcomes limitations of traditional econometric methods by simulating micro-level structures, and multi-factor feedback mechanisms, thereby enhancing precision in causal inference. Using Hainan Island as an empirical case study, it reveals dynamic evolution of carbon neutrality under tourism growth scenarios and their interaction characteristics. These findings not only provide an empirical basis for optimizing carbon neutrality governance policies in Hainan but also establish a portable analytical framework for emerging tourist destinations, demonstrating substantial practical significance.

Literature review

Tourism and sustainable development. Existing research initiatives predominantly examine the interplay between ESG factors and their impacts on SDGs. First, the environmental component constitutes a pivotal dimension of the ESG framework, incentivizing corporate resource allocation and operational efforts to enhance environmental performance (Işık et al., 2024e). This effort aims to advance SDGs related to environmental quality and associated outcomes (Roscoe et al., 2019). Second, social governance encompasses corporate policies designed to strengthen stakeholder engagement and safeguard rights, welfare, and assets during business operations (Siakwah et al., 2020). These social accountability mechanisms serve dual purposes: regulating corporate conduct and addressing public concerns central to the SDGs, including rights preservation, welfare enhancement, and livelihood improvements (Li et al., 2018a). Third, effective governance is critical to advancing the SDGs through transparent institutions and inclusive decision-making processes, as robust governance systems enable resource mobilization and policy implementation to address multifaceted challenges outlined in the SDGs (Işık et al., 2024e). However, conventional ESG frameworks present an incomplete conceptualization of sustainability by omitting economic considerations (Işık et al., 2024f). Integrating economic dimensions is imperative, as resource allocation efficiency, green investment scalability, and innovation-driven growth remain foundational to balancing sustainability transitions with developmental imperatives. Within the ECON-ESG framework, researchers have empirically examined regional sustainability impacts of its constituent factors across diverse geographies (Hieu & Hai, 2023; Sadiq et al., 2023; Gidage & Bhide, 2024). Under intensifying climate change pressures, climate governance has emerged as a central priority in SDGs pursuit, playing a pivotal role in environmental sustainability strategies. It has been systematically applied to advance practices in energy efficiency optimization (Işık et al., 2024f), carbon emission mitigation (Işık et al., 2025), and ecological footprint reduction (Işık et al., 2024c).

As an industry uniquely positioned to facilitate socio-cultural exchange, tourism bears significant responsibility for sustainable management across economic, social, and environmental dimensions (Woo, 2023). Sustainable tourism seeks to address the impacts of tourism activities on local ecosystems, socio-cultural and economic systems (Mason et al., 2023), thus aligning with the core concepts of sustainability: environmental sustainability prioritizes ecosystem integrity through conservation practices (Holden, 2016), social sustainability emphasizes community well-

being through cultural preservation and equitable development (Mowforth & Munt, 2015), while economic sustainability focuses on employment security, income stability, and regional prosperity (Hall, 2021). Although tourism receives limited explicit mention in the SDGs, its operational paradigms exhibit intrinsic congruence with these global objectives (Mason et al., 2023). Within the ECON-ESG framework, scholarly attention initially centered on tourism's economic impacts. Empirical studies confirm its capacity to generate foreign exchange earnings for capital goods imports, stimulate employment growth, enhance tax revenues, and drive economic efficiency through market competition (Buallay et al., 2022). However, growing recognition of tourism's ecological externalities (e.g., resource depletion and greenhouse gas emissions), changing business landscape, and heightened stakeholder expectations for corporate accountability have prompted integration of ESG principles into operational and strategic frameworks of tourism enterprises (Ye et al., 2025; Back et al., 2024; Legendre et al., 2024). This paradigm shift enables them to align profitability with sustainability imperatives, utilizing ESG metrics as non-market strategies to fulfill corporate social responsibilities, enhance operational performance, and foster visitor engagement with sustainability practices on a broader scale (Chen et al., 2022; Sim & Kim, 2025; Shin et al., 2025; Zheng et al., 2025). Given tourism's catalytic role in operationalizing ECON-ESG factors, this study adopts an ECON-ESG lens to investigate the interplay between tourism development and carbon neutrality transitions within CNTDR systems.

Tourism and regional carbon neutrality. Carbon neutrality, aimed at achieving net-zero emissions, does not necessitate the complete elimination of carbon emissions but rather focuses on equalizing emissions with absorption (Liu et al., 2022a). The pathways to achieving carbon neutrality encompass two fundamental directions: reducing carbon sources and enhancing carbon sinks (Yang et al., 2024). Therefore, the impact of tourism on regional carbon neutrality would be explored from these two aspects.

Climate change has elevated low-carbon tourism as a critical research focus in sustainability studies. Researchers employ life cycle assessment and input-output analysis frameworks to quantify tourism-related carbon emissions (Zha et al., 2021). Empirical evidence confirms the tourism sector's role as a key emission driver, with its rapid global expansion significantly exacerbating carbon footprints across diverse regions (Sun et al., 2024; Gössling et al., 2024). However, conventional accounting methodologies, while quantifying absolute emissions, lack systemic consideration of tourism's multifaceted interactions within regional carbon cycles. This limitation underscores the necessity for comprehensive investigations into tourism's complex interdependencies with localized emission dynamics (Zhang, 2022).

Scholarly investigations have employed diverse econometric models to assess tourism's impact on regional carbon emissions across geographical contexts. Divergent empirical findings emerge: studies in the European Union (Dogan & Aslan, 2017), leading tourism destinations (Alam & Paramati, 2017), and G7 economies (Ahmad et al., 2022a) identify emission-reduction effects from tourism development. Conversely, analyses of Nepal (Nepal et al., 2019), BRICS nations (Danish & Wang, 2018), and OECD countries (Dogan et al., 2017) report tourism-induced emission escalation. examinations of the environmental kuznets curve (EKC) framework further reveal nonlinear dynamics in tourism-emission relationships. This variability stems not only from destination-specific developmental stages (Paramati et al., 2017) but also contextual socio-economic factors (Zaman et al.,

2016). While academic consensus remains elusive, these collective efforts have systematically integrated tourism into regional carbon emission research paradigms. Importantly, these mixed findings highlight the necessity to further investigate the complex interaction mechanisms between tourism and carbon emissions, aiming to comprehensively understand the roots of such nonlinear dynamics and reduce uncertainties.

On the other hand, regional carbon neutrality necessitates strengthening carbon sequestration capacities (Liu et al., 2022a). Current research on tourism's environmental externalities disproportionately emphasizes emission sources, with limited investigation into its carbon sink impacts (Tong & Zhang, 2023). Gössling (2002) observes that tourism infrastructure development—driven by accommodation and transportation demands—frequently induces direct landscape modifications. Subsequent investigations have also assessed the effects of various tourism models, such as rural (Li et al., 2020), urban (Langemeyer et al., 2015), and ecotourism (Chen, 2020), on land use and ecosystems. Given land-use changes' critical role in regulating ecosystem carbon cycles (Ye & Chuai, 2022; Xu, 2024), tourism-driven spatial transformations likely influence regional carbon sink dynamics.

Carbon Capture and Storage (CCS) technology constitutes a pivotal component of global decarbonization strategies (Zhang, 2021; Yang et al., 2024). IEA (2020) emphasizes that climate models cannot achieve mid-century carbon neutrality targets without CCS implementation. This imperative has prompted scholars to incorporate CCS into regional carbon neutrality frameworks, exploring integrated mitigation pathways (Hu & Wu, 2023; Liu et al., 2022a). Given the critical role of CCS technology in reducing emissions, it is imperative to include it in the carbon neutrality analysis framework for tourism-dependent regions.

Decomposition approach and system dynamics. Factor decomposition has established itself as a critical methodology for analyzing energy and emission transition drivers (Roinioti & Koroneos, 2017). It has evolved into two methodologies: structural decomposition analysis (SDA), which employs input-output matrices for macroeconomic assessments, and index decomposition analysis (IDA), tailored for longitudinal sector-specific investigations (Rose & Casler, 1996). Su and Ang (2012) conducted a comparison of these approaches, highlighting IDA's superior applicability in energy consumption and environmental studies due to its methodological flexibility. Within IDA frameworks, the LMDI method has become the predominant technique due to its technical maturity and different forms, leveraging its methodological robustness and adaptability in decomposing temporal datasets into underlying factors (Zhang & Da, 2015). The LMDI approach distinguishes itself through its ability to concurrently analyze multiple interdependent variables, enabling comprehensive examination of complex system dynamics (Huang et al., 2023). LMDI has been used extensively to decompose carbon emissions at various scales (Dong et al., 2020; Zhang & Liu, 2024) and in various sectors (Shui et al., 2024; Yang & Guo, 2024). However, existing studies have focused predominantly on static analysis of influencing factors, while the dynamic interactions between tourism development and determinants of regional carbon neutrality remain unexamined.

We therefore integrate SD, a methodology for investigating causal relationships and dynamic interactions in complex systems (Dong et al., 2012). This methodological coupling offers synergistic advantages: empirical insights from LMDI decomposition establish mathematically robust foundations for SD

modeling, while SD simulations elucidate the interactions between tourism development and carbon neutrality determinants within the complex CNTDR system (Yang et al., 2021; Luo et al., 2023). To further elaborate, LMDI-identified drivers inform SD's causal loop construction, enabling the identification of endogenous behaviors arising from tourism–environment interactions.

Carbon emission simulation research serves as a scientific foundation for setting carbon reduction targets and evaluating the effectiveness of emission reduction strategies (Feng et al., 2013). Due to its adaptability in addressing the complexities of carbon emission systems (Li et al., 2018b), many scholars have used system dynamics for regional carbon emission forecasting and scenario simulation. These studies primarily focus on national (Yang et al., 2021), regional (Luo et al., 2023), and urban scales (Gu et al., 2019). Moreover, some researchers have integrated carbon sinks into their models, constructing regional carbon neutrality simulation models that provide a scientific basis for achieving carbon neutrality goals and fostering regional sustainable development (Wen et al., 2022; Zhan et al., 2024).

In the limited studies on low-carbon tourism system simulation, scholars predominantly construct low-carbon tourism SD models from the perspective of the tourism industry itself (Luo et al., 2020) and its subdivisions (Tong et al., 2024). However, these studies offer limited reference value for the comprehensive low-carbon management of destinations. In existing studies simulating the environmental impacts of tourism, scholars have primarily focused on the dynamic changes in environmental pollution (e.g., wastewater and solid waste) and ecosystem services at destinations, while neglecting the progress towards carbon neutrality (Zhang et al., 2015; He et al., 2018; Hafezi et al., 2021). Consequently, utilizing systems thinking to understand the complex mechanisms between tourism and regional carbon neutrality remains unexplored. Currently, a simulation model that reflects the various interactions among elements within the CNTDR system, and the resulting endogenous behaviors, has not been constructed.

Framework development

This study proposes an integrative framework incorporating tourism into regional carbon neutrality assessments, examining the CNTDR system's dynamic structure and behavior to systematically elucidate interaction mechanisms among core subsystems. The methodology employs a five-stage iterative modeling protocol—problem articulation, dynamic hypothesis formulation, simulation model construction, model validation, and simulation with result analysis—thereby ensuring analytical robustness (Sterman, 2002). The procedure of the SD approach applied in this research is shown in Fig. 1.

The definition of carbon neutrality in tourism-dependent region system. Problem articulation necessitates delineating the system boundary for CNTDR, with tourism constituting the central subsystem that dynamically interacts with other components. We model tourism development through its core indicators—tourist arrivals and tourism income—along with their determinants (Sun et al., 2022). Carbon neutrality is structurally decomposed into emission sources and sinks. For the former, we focus on energy-related carbon emissions given their dominant contribution to greenhouse gases (Yang et al., 2021). Given the residential sector's escalating role in energy consumption emissions, we further stratify emissions into industrial and residential subsystems (Ma et al., 2019). Carbon sinks are operationalized through natural sequestration (land-use) and anthropogenic

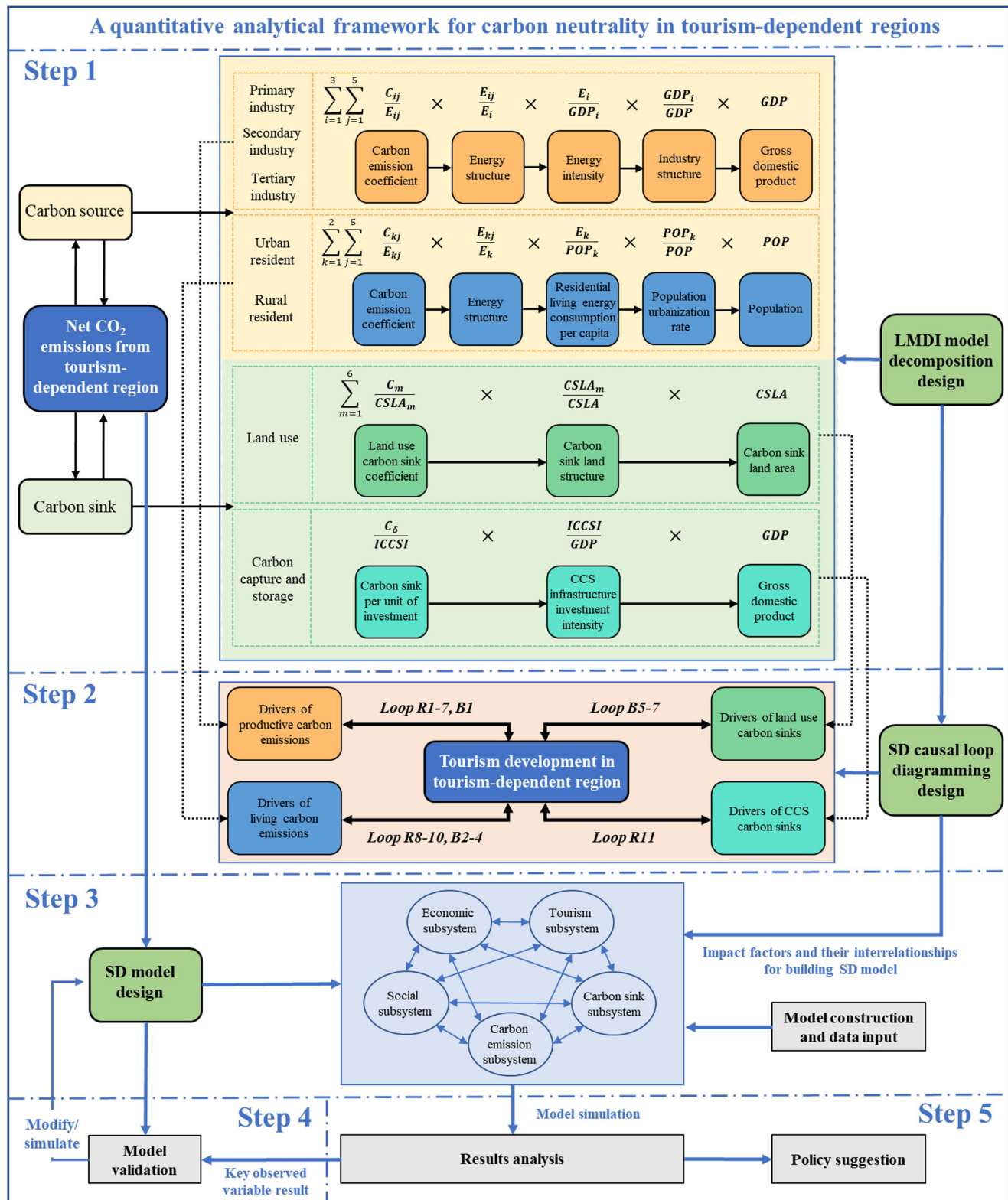


Fig. 1 Research framework diagram.

mitigation measures (CCS infrastructure) (Hu & Wu, 2023), with a methodology based on the guidelines of IPCC (2006) and relevant literature, and calculation specifications detailed in Appendix A1. Further, key system drivers are identified through an extended LMDI decomposition model across sectors (see Appendix A2 for details).

Causal loop diagram development. The CNTDR represents a complex dynamic system that integrates the internal evolution of tourism and the external shifts in the macro environment, including interactive effects between tourism and the identified driving factors. A causal loop diagram (CLD) serves as a modeling tool for system dynamics that highlights the core elements

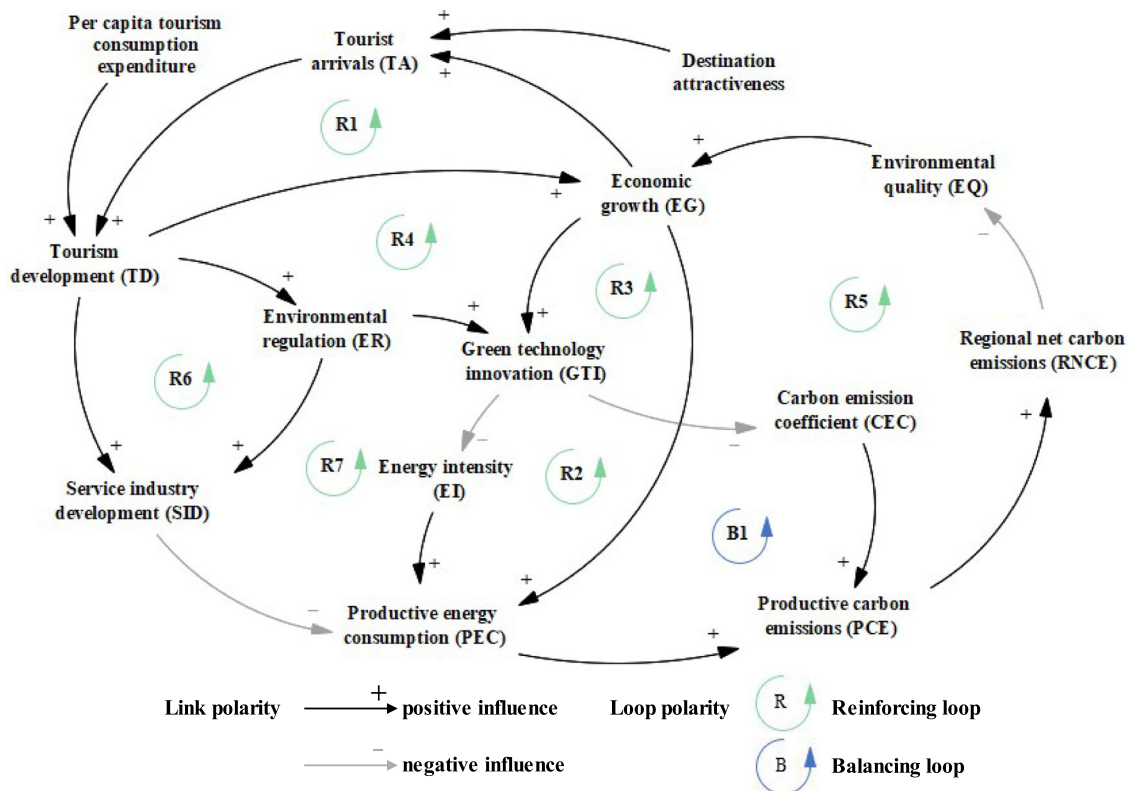


Fig. 2 Causal loop diagram of carbon emissions drivers by industrial sector.

of a system and the behavior resulting from their interactions (Crabolu et al., 2023). Feedback loops are categorized as either reinforcing or balancing: a reinforcing loop amplifies the effects within the system as all factors respond similarly, whereas a balancing loop mitigates these effects by producing outcomes in the opposite direction. Therefore, employing CLD, we analyze the interconnections between tourism and ECON-ESG factors to map transmission pathways through which tourism influences carbon neutrality drivers.

Causal loop diagram of productive carbon emissions. Figure 2 depicts the feedback loops between the tourism and the driving factors of carbon emissions in the industrial sector, including economic growth, energy intensity, carbon emission coefficient, and industrial structure. This illustration encompasses seven reinforcing feedback loops and one balancing feedback loop. The variable abbreviations are shown in the following figure. The same analysis applies below.

(1) Economic growth

Promoting tourism development and economic growth is crucial for enhancing the well-being of local residents (Rivera et al., 2016). However, the continuous increase in energy consumption driven by economic development is often inevitable (Zhang et al., 2022), forming *Loop R1* and *Loop B1*.

Loop R1: $TD \rightarrow EG \rightarrow TA \rightarrow TD$. Numerous studies have confirmed the bidirectional causal relationship between tourism development and economic growth (Yang & Fik, 2014; Zhang & Gao, 2016). On one hand, tourism development enhances the economic level of a destination. On the other hand, an improved economic level augments the attractiveness and hospitality capacity of the destination, consequently drawing more tourists and further promoting tourism development.

(2) Energy intensity

Green technology innovation is a pivotal strategy for reducing energy intensity (Miao et al., 2024). Environmental regulation and economic growth serve as the primary drivers of green technological innovation, establishing the following feedback loops.

Loop R2: $TD \rightarrow ER \rightarrow GTI \rightarrow EI \rightarrow PEC \rightarrow PCE \rightarrow RNCE \rightarrow EQ \rightarrow EG \rightarrow TA \rightarrow TD$. Ensuring a good ecological environment is essential for the sustainable development of tourism, leading destination governments to implement stringent environmental regulations (Wang et al., 2019). Environmental regulation involves government intervention, either directly or indirectly, in enterprise resource utilization and pollution emissions to protect the environment and conserve resources (Zhou et al., 2021). According to the “Porter Hypothesis,” environmental regulation increases production costs for enterprises (such as pollution fees and investments in pollution control), thereby incentivizing green technology innovation (Porter & Linde, 1995). This innovation reduces the destination’s energy intensity and decreases productive carbon emissions.

Loop R3: $EG \rightarrow GTI \rightarrow EI \rightarrow PEC \rightarrow PCE \rightarrow RNCE \rightarrow EQ \rightarrow EG$. The economic growth spurred by tourism development (*Loop R1*) provides more financial support for green technology innovation at the destination. This, in

turn, improves the destination's energy utilization efficiency and reduces carbon emissions from the industrial sector (Apergis, 2016).

- (3) Carbon emission coefficient (electricity for the industrial sector)

Loop R2 and *R3* indicate that tourism development can indirectly promote green technology innovation. Besides reducing energy intensity, green technology innovation can also achieve emission reduction by lowering the carbon emission coefficient of energy, primarily through the power sector (Yan & Fang, 2015). This interaction establishes additional feedback loops.

Loop R4: TD → ER → GTI → CEC → PEC → PCE → RNCE → EQ → EG → TA → TD.

Loop R5: EG → GTI → CEC → PEC → PCE → RNCE → EQ → EG.

- (4) Industrial structure

Industrial structure upgrading is an important measure for promoting carbon reduction (Li & Lin, 2014). Tourism development can impact the destination's industrial structure through the factor allocation effect (*Loop R6*) and the environmental regulation effect (*Loop R7*).

Loop R6: TD → SID → PEC → PCE → RNCE → EQ → EG → TA → TD. Tourism development can raise local price levels and occupy large amounts of land and labor, leading to an increase in factor prices, which is unfavorable for the development of agriculture and manufacturing (Dwyer et al., 2003). On the other hand, apart from the crowding-out effect, tourism, due to its strong linkage with related industries, promotes the development of productive services (Sun et al., 2022). These dual effects collectively drive the upgrading of the destination's industrial structure. Generally, the tertiary industry operates more cleanly, thereby contributing to the reduction of regional carbon emissions (Li & Lin, 2014).

Loop R7: TD → ER → SID → PEC → PCE → RNCE → EQ → EG → TA → TD. Tourism development can also enhance environmental regulations, compelling pollution-intensive enterprises to relocate or accelerate the elimination of high-input, high-emission production methods, thereby promoting regional carbon reduction (Sun et al., 2022).

Causal loop diagram of living carbon emissions. Figure 3 illustrates the feedback loops between tourism development and the driving factors of carbon emissions in the residential sector, influenced by *Loop R1*. These factors include population, residential living energy consumption per capita, population urbanization rate, and carbon emission coefficient. The figure includes three reinforcing feedback loops and three balancing feedback loops.

- (1) Population

Residential sector carbon emissions constitute a significant component of regional carbon emissions, impacting the carbon neutrality process. Population size is the primary factor influencing residential sector carbon emissions (Wang et al., 2017), establishing the following feedback loops.

Loop B2: TA → POP → LEC → LCE → RNCE → EQ → EG → TA. Seasonal tourism migrants flocking to the destination increase the local population size (Wu et al., 2018). Additionally, tourism, being a labor-intensive industry (Zha & Li, 2017), drives up the demand for labor as tourist visits grow, thereby promoting labor migration to the destination (Salazar, 2022). Consequently, these factors contribute to population growth, leading to increased residential energy consumption and higher carbon emissions from the residential sector.

Loop R8: TA → POP → LS → TA. The increase in tourist visits drives population growth (*Loop B2*), subsequently boosting the local labor supply. As a crucial input factor, this expanded labor supply further promotes tourism development (Stauermann & Kumar, 2017).

- (2) Residential living energy consumption per capita
Residential living energy consumption per capita is another major factor affecting residential carbon emissions (Gu et al., 2013), forming the following loop.

Loop B3: EG → GP → ECP → LEC → LCE → RNCE → EQ → EG. Tourism development promotes economic growth (*Loop R1*), which in turn improves residents' living standards. As residents' consumption capacity increases (e.g., the use of private cars and high-power electrical appliances), residential energy consumption per capita rises, leading to further increases in living carbon emissions (Wang & Yang, 2014).

- (3) Population urbanization rate

Generally, urban lifestyles have higher carbon emission intensity compared to rural lifestyles (Wang & Yang, 2014). Therefore, the urbanization rate significantly impacts residential carbon emissions, forming the following loop.

Loop B4: EG → GP → PUR → LEC → LCE → RNCE → EQ → EG. Tourism development promotes economic growth (*Loop R1*), which in turn drives urbanization (Moomaw & Shatter, 1996). This process exacerbates carbon emissions from the residential sector.

- (4) Carbon emission coefficient (electricity for the residential sector)

As economic growth accelerates, household income rises, and urbanization advances, the proportion of electricity in residential energy consumption is expected to increase gradually (Khanna et al., 2016). Tourism development, by promoting green technology innovation and reducing the carbon emission coefficient of electricity (as described in *Loop R4* and *Loop R5*), can further establish the following loops.

Loop R9: TD → ER → GTI → CEC → LEC → LCE → RNCE → EQ → EG → TA → TD.

Loop R10: EG → GTI → CEC → LEC → LCE → RNCE → EQ → EG.

Causal loop diagram of carbon sinks. Figure 4 illustrates the feedback loops between tourism development and both carbon sink land area and CCS, influenced by *Loop R1*. This includes one reinforcing feedback loop and three balancing feedback loops.

- (1) Land use carbon sinks

Land resources, as the carrier of economic activities, are an indispensable factor of production and crucial for global climate change and the carbon cycle (Cao & Yuan, 2019). According to *Loops R1*, *R6*, and *R7*, tourism development promotes economic growth and industrial structure upgrading (i.e., rapid development of non-agricultural industries). This process fosters the expansion of construction land (Yanbo et al., 2019), thereby reducing the area of carbon sink land and impairing the carbon sink capacity of the destination. The following three loops are formed.

Loop B5: TD → SID → NAG → CSLA → LUCS → RNCE → EQ → EG → TA → TD.

Loop B6: TD → EQ → SID → NAG → CSLA → LUCS → RNCE → EQ → EG → TA → TD.

Loop B7: EG → NAG → CSLA → LUCS → RNCE → EQ → EG.

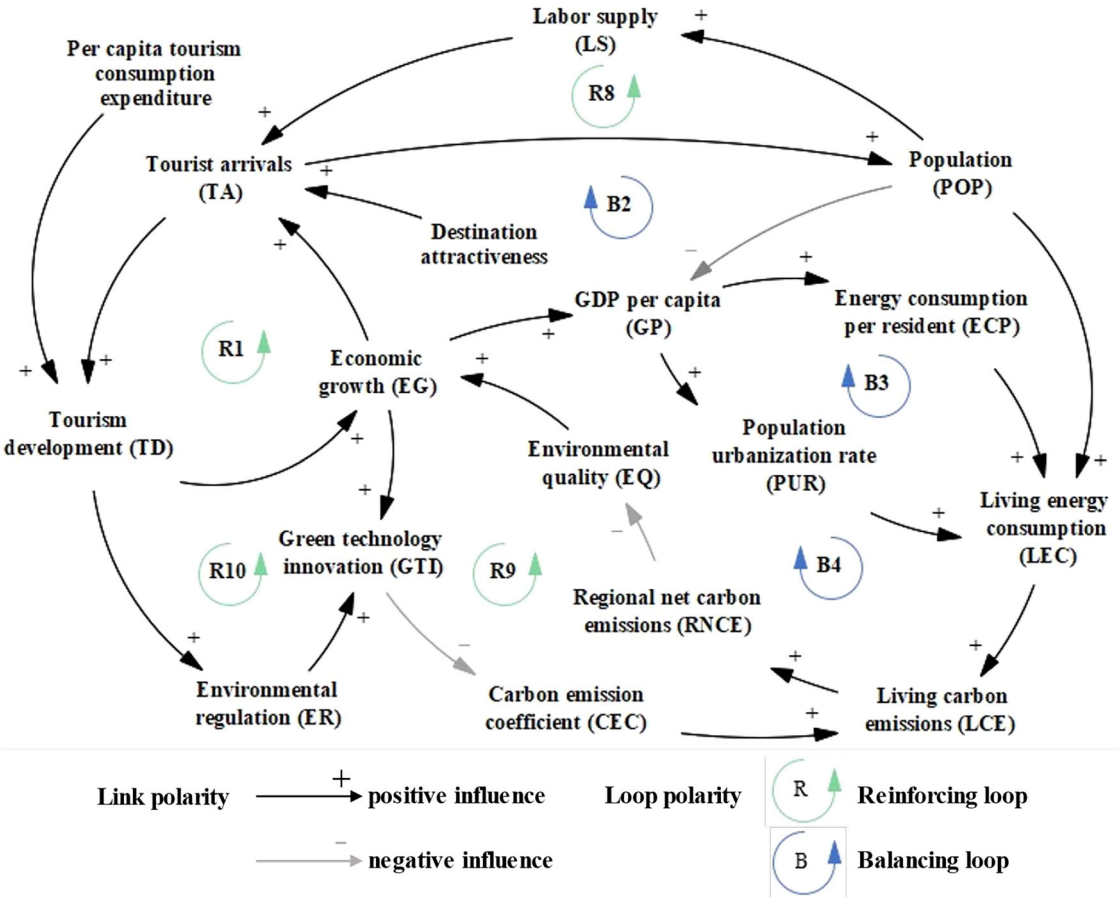


Fig. 3 Causal loop diagram of carbon emissions drivers by residential sector.

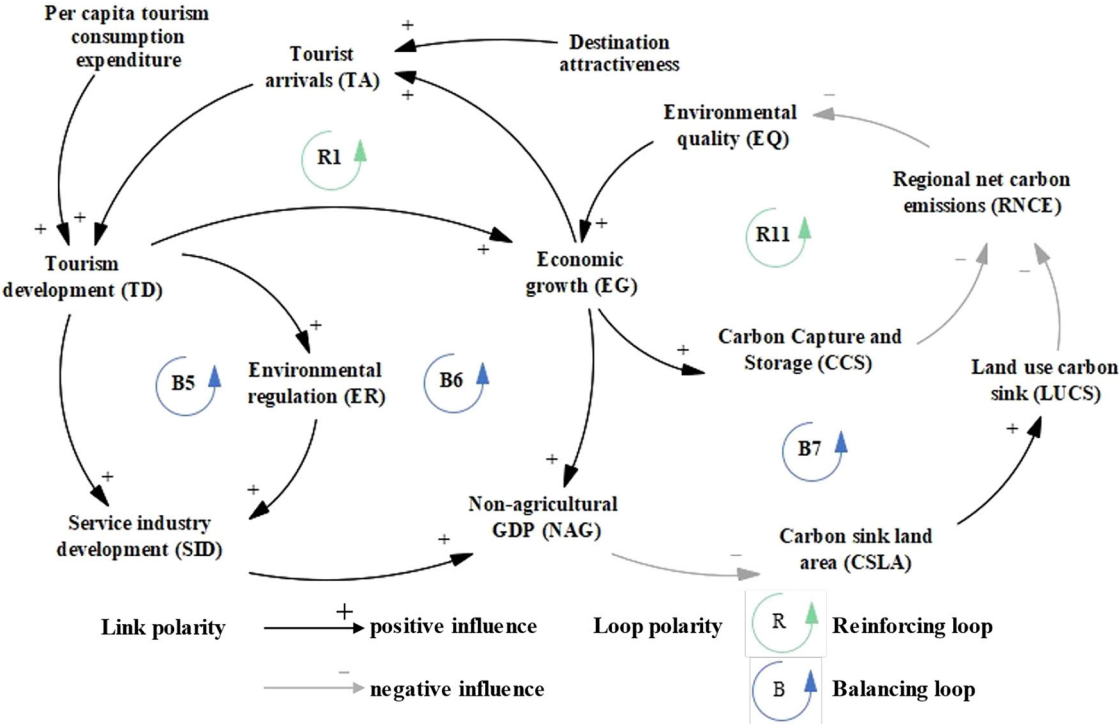


Fig. 4 Causal loop diagram of carbon sinks drivers.

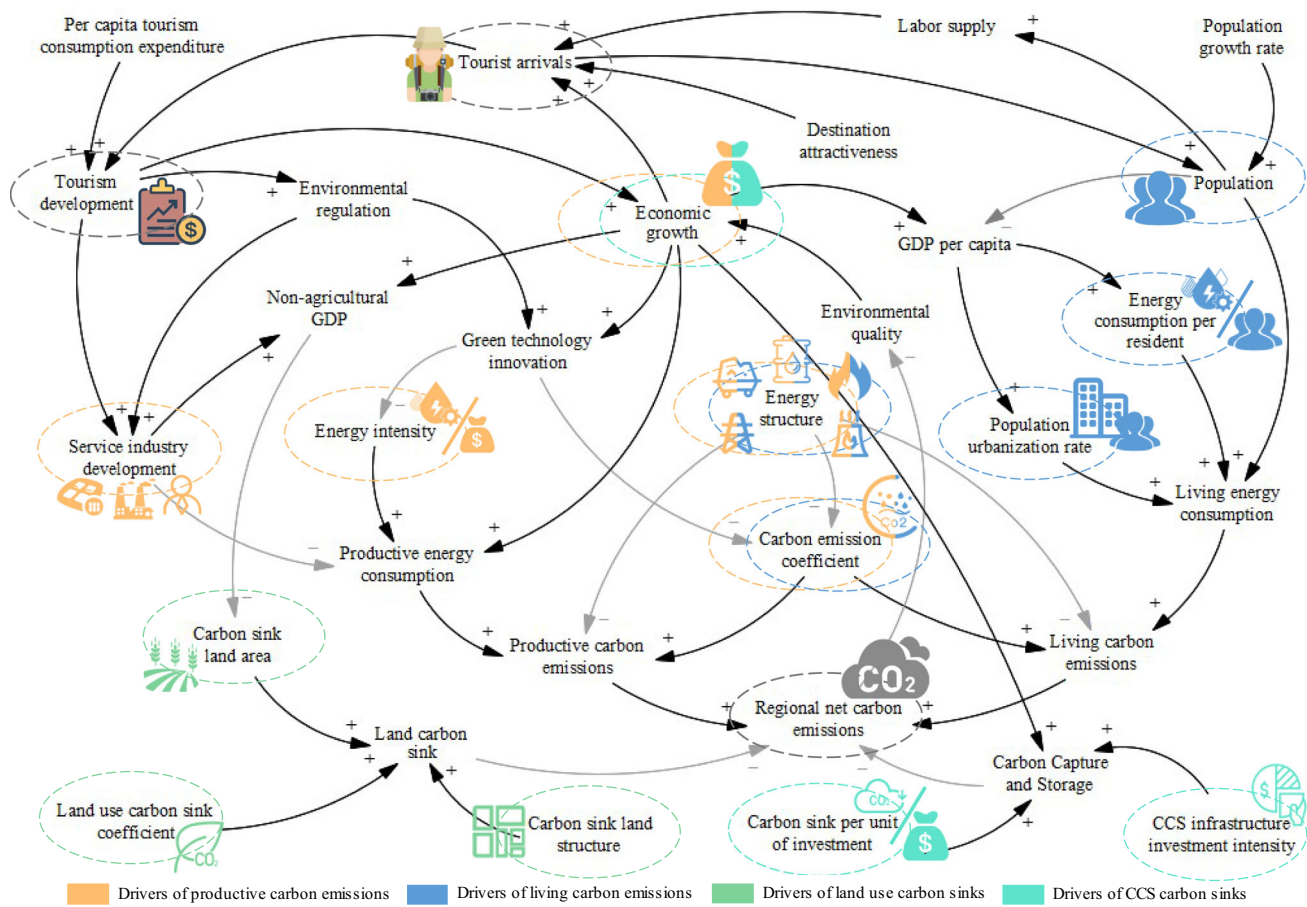


Fig. 5 Complete causal loop diagram of carbon neutrality in tourism-dependent regions.

(2) CCS carbon sinks

Loop R11: $EG \rightarrow CCS \rightarrow RNCE \rightarrow EQ \rightarrow EG$. Regarding CCS carbon sinks, tourism development catalyzes economic growth (*Loop R1*), which subsequently increases financial resources available for CCS technology adoption and project construction at the destination (Yang et al., 2021). This enhancement in financial backing ultimately boosts the region's carbon capture capacity, thereby establishing a feedback loop.

Causal loop diagram of carbon neutrality in tourism-dependent regions. Based on the preceding analysis, the comprehensive CLD of CNTDR is integrated into Fig. 5. This diagram further includes the other drivers that impact regional carbon neutrality. Although these drivers do not directly establish a complete feedback loop within the system, they serve as significant exogenous factors that play a crucial regulatory role in the previously mentioned constructed loops. For example, the energy structure is mainly dominated by external policy regulations and energy resource endowments, making it difficult to capture through endogenous feedback loops within regional systems (Su & Tan, 2023). This CLD will guide the construction of the subsequent stock and flow diagram.

Stock and flow diagram development. Once the system CLD has been confirmed, a stock and flow diagram (SFD) can be developed to simulate complex dynamic behaviors (Sternan, 2002). Therefore, based on the final CLD, we utilized AnyLogic software to develop the SFD for CNTDR (Fig. 6). The

model is designed to provide an actionable open-access analytical platform for achieving carbon neutrality in such regions. It comprises five interconnected subsystems: tourism, economic, social, carbon sink, and carbon emission. Within the system, elements are categorized into four types: stocks, flows, variables, and constants. Stocks represent the cumulative states of the elements; flows denote the rates of input or output relative to the stocks; variables define dynamic relationships among the elements; constants remain unchanged over time. The abbreviations and types of elements are detailed in Appendix A3.

Tourism subsystem. The tourism subsystem examines the dynamic changes in tourist arrivals and tourism development (i.e., total tourism income). The number of tourist arrivals depends on multiple factors, including tourist attractions, input of production factors, transportation infrastructure, tourism facilities, ecological environment, and the level of economic development. Tourist attractions are essential for supporting local tourism development, as they form the core of tourism products (Rosentraub & Joo, 2009). Labor and capital, significant production inputs in this comprehensive, cross-sector industry, are represented by the number of tertiary industry employees and fixed asset investments in the tertiary sector (Sun et al., 2020). Transportation infrastructure is a prerequisite for tourism development, as enhancements in transportation conditions significantly improve the accessibility and connectivity of destinations (Khadaroo & Seetanah, 2008). Tourism facilities reflect the destination's capacity to accommodate tourists (Zhang et al., 2011). The urban green land area per capita is used to gauge

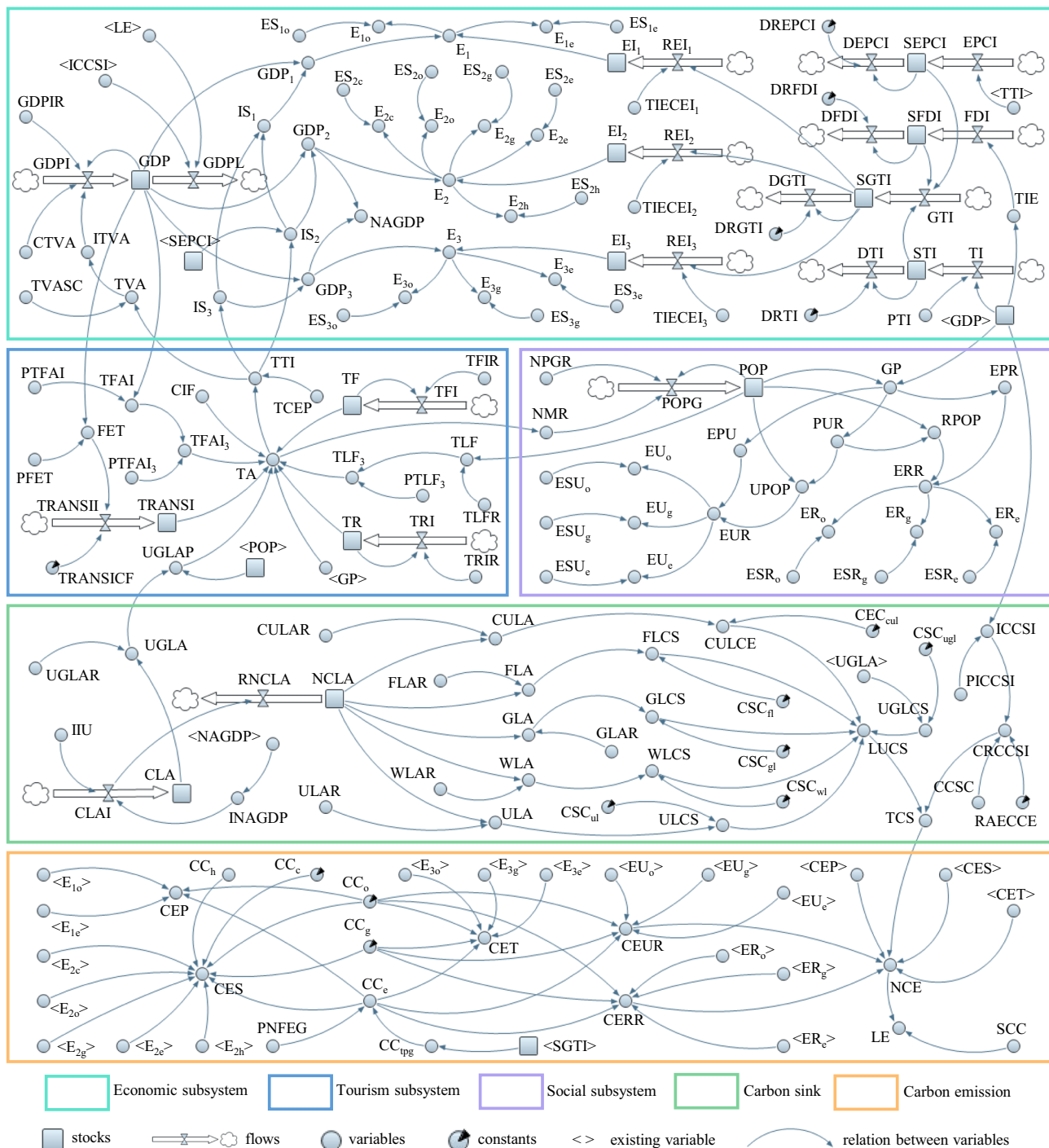


Fig. 6 Stock and flow diagram of carbon neutrality in tourism-dependent regions.

environmental quality, with public urban green spaces providing essential ecosystem services, improving air quality, reducing climate impacts, and offering recreational spaces for residents and tourists (Fan et al., 2017). Economic development improves the quality of tourism-related infrastructure and services, inherently enhancing the destination's competitiveness (Albaladejo et al., 2014). Total tourism income results from multiplying the number of tourist arrivals by the tourism consumption expenditure per capita.

It should be noted that this subsystem design is applicable to regions where tourism constitutes a significant economic activity or holds developmental potential, with a foundation in market-

driven mechanisms and relatively stable geopolitical/socio-environmental conditions. The applicability of these elements remains context-dependent. Specific implementations may include: prioritizing attractions that better represent destination uniqueness and visitor appeal; selecting transportation infrastructure with maximal connectivity impacts. Furthermore, dynamic adjustments could be made according to destination typologies. For instance, agricultural tourism destinations may require integration of primary industry inputs with parallel consideration of informal accommodation platforms (e.g., Airbnb), while ecotourism zones may consider biodiversity conservation to reflect environmental quality.

Economic subsystem. The economic subsystem primarily simulates economic growth, industrial structure, green technology innovation, and the energy intensity and consumption of the production sector. This model demonstrates heightened effectiveness in economies where integrated tourism-industry linkages exist, more comprehensive energy data is available, and proactive climate policies are implemented to ensure that regulatory frameworks and green investments drive environmental benefits.

Economic growth consists of the incremental value-added by both the tourism and non-tourism sectors. Specifically, following the study by Meng et al. (2016), the total tourism income is converted into tourism value-added, thereby calculating the annual increment of tourism value-added. The incremental value-added by non-tourism is determined by subtracting the tourism value-added increment from the overall GDP increment. Additionally, within the carbon sink subsystem, investments in CCS infrastructure, along with the social cost of carbon (SCC) in the carbon emission subsystem, moderate the GDP growth rate (Yang et al., 2021; Li et al., 2021a). The SCC is a critical tool for economic analysis of climate policies, representing the economic loss caused by the additional emission of one ton of CO₂ (Ricke et al., 2018). Industrial structure is influenced by tourism development and environmental regulations. Environmental regulations, technology investments, and foreign direct investment (FDI) drive green technology innovation. Tourism boosts environmental regulation intensity, while GDP growth propels technology investments and FDI (Du et al., 2021). Improvements in energy intensity within the production sector hinge on green technology advances and the innovation elasticity coefficients (Li et al., 2021b). Energy consumption by the three industries is calculated based on the value-added by each industry, their energy intensity, and the energy consumption structure.

Social subsystem. The social subsystem simulates key factors including population size, urbanization rate, and residential energy consumption. Population size is influenced by the destination's natural growth rate and net migration rate, the latter of which is affected by tourist arrivals. The urbanization rate and per capita residential energy consumption for urban and rural residents are modeled based on the level of economic development (Yang et al., 2021). Additionally, the energy consumption of urban and rural residents varies according to their population sizes, residential energy consumption per capita, and the type of energy used.

The applicability of this subsystem is constrained by two conditions: On the one hand, population dynamics require destinations with stable tourism-driven migration patterns, where the relationship between tourist arrivals and net migration rates is governed by socioeconomic factors. This applies to regions with established tourism sectors and open economies. On the other hand, residential energy calculations necessitate separate urban and rural data on both energy types and consumption.

Carbon sink subsystem. The carbon sink subsystem models land use and CCS carbon sinks. In terms of land use carbon sinks, the area of carbon sink land and construction land are inversely related (Xing et al., 2019). The area of construction land is determined by non-agricultural GDP and land use intensity (i.e., the area of construction land per unit of non-agricultural industrial value added). Additionally, urban green land, a critical carbon sink, is quantified based on its proportion within construction land areas. Regarding CCS, the effectiveness of these carbon sinks is shaped by investment levels and costs. With increasing investments and technological advancements, CCS technology becomes more cost-effective, enhancing carbon sequestration efficiency per investment unit. It is important to

note that, unlike improvements in energy efficiency, CCS provides environmental benefits rather than direct economic benefits (excluding additional measures such as carbon utilization and carbon markets). Therefore, investment in CCS might result in a reduction in the GDP growth rate (Yang et al., 2021).

Notably, the subsystem components operate under the following boundary conditions: the correlation between construction land use and non-agricultural GDP, coupled with its competition with carbon sink lands, is more applicable to tourism-dependent economies in accelerated industrialization-urbanization phases. CCS effectiveness assumes policy-driven investment continuity, with potential carbon sequestration deviations under technological lock-in or fiscal instability scenarios. Further, the modeled GDP suppression effect of CCS presumes non-monetized environmental benefits, necessitating recalibration of cost-benefit parameters if carbon markets or eco-compensation mechanisms are institutionalized.

Carbon emission subsystem. The carbon emission subsystem models the energy carbon emission coefficient, carbon emissions from the industrial and residential sectors, the destination's net carbon emissions, and the resulting environmental damage. The carbon emission coefficient for fossil fuels remains constant, whereas the coefficient for heat adjusts dynamically, based on established references (Gu et al., 2019). The coefficient for electricity is calculated by considering the proportion of non-fossil energy in power generation alongside the carbon emission coefficient for thermal power (Yan & Fang, 2015). The carbon emissions from various types of energy consumption in the industrial and residential sectors (simulated by the economic subsystem and the population subsystem) are calculated by multiplying the energy consumption by the corresponding energy carbon emission coefficient. The net carbon emissions of the destination reflect the difference between the total carbon emissions and the carbon sinks. Environmental damage is determined by the SCC and the regional net carbon emissions, ultimately impacting the destination's economic growth.

Uncertainties in this subsystem stem primarily from two limitations: Electricity emission coefficient calculations rely on the disclosure of power mix and emission coefficient for thermal power data within unified grid dispatch zones. In addition, the electricity supply-demand equilibrium assumptions require supplemental adjustments when applied to regions with substantial external power dependencies.

Framework validation and application

Case study application. To evaluate the effectiveness of the quantitative analytical framework for CNTDR, we selected Hainan, China (108°37'–111°03'E, 18°10'–20°10'N) as a representative case for empirical validation (Fig. 7). As China's only tropical island province, Hainan boasts unique tourism resources and a favorable climate, establishing it as a premier tourist destination nationally. The central government has consistently regarded tourism as a pillar industry in Hainan's national economic system and designated the entire province as a national all-for-one tourism demonstration area. Since the establishment of the Hainan International Tourism Island, the tourism industry has developed rapidly. Total tourism revenue grew from 257.6 billion CNY in 2010 to 1057.8 billion CNY in 2019, while the tourism industry dependency ratio climbed from 12.75% to 19.84%. Despite severe impacts from the COVID-19 pandemic, this ratio remained above 15% during 2020–2021.

Data sources and parameter settings. Given the rapid development of tourism following the establishment of the Hainan

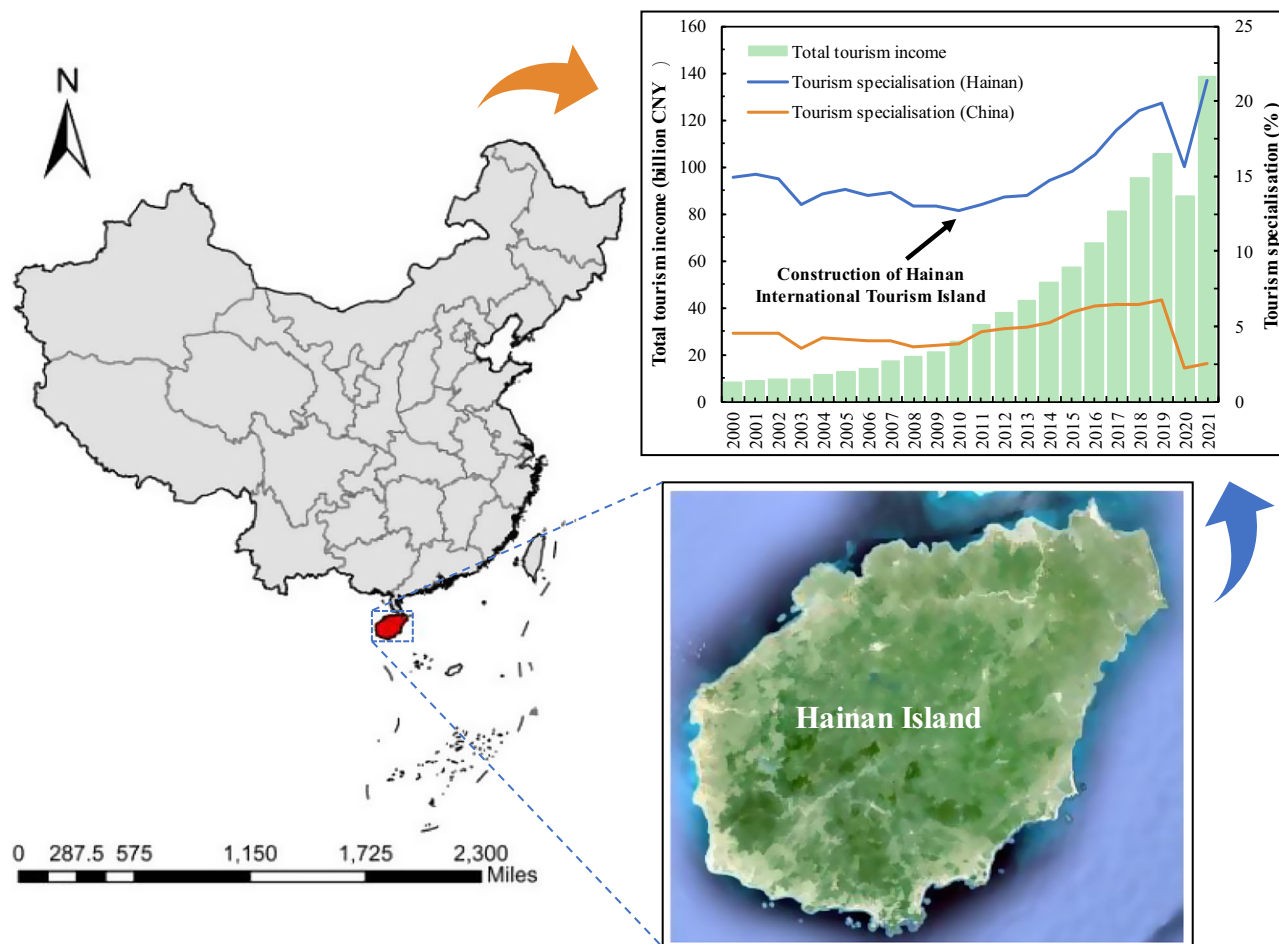


Fig. 7 Location of Hainan Island, China.

International Tourism Island and the availability of data, the period from 2010 to 2021 was selected for model validation, with a simulation time step of one year. This study quantified parameters for the SD model using multi-source datasets.

Tourism-related data, including tourist arrivals, total tourism income, tourism facilities (the total number of tourist hotels and travel agencies) (Wang et al., 2020), tertiary industry factor inputs, and transportation infrastructure (highway mileage) (Zhang et al., 2015), were sourced from the Hainan Statistical Yearbook (HNBS, 2011–2022). Tourism resources were quantified by 4A and 5A-rated scenic spots (Wang et al., 2020), documented in the A-rated Scenic Areas Directory issued by DTCRTSHN (2024).

For economic and social dimensions, energy-related data, including sectoral and residential energy consumption and energy structure, were derived from energy balance sheets in the China Energy Statistical Yearbook (NBS, 2011–2022). According to the International Patent Classification (IPC) code of green patents listed in the green patent list provided by the World Intellectual Property Organization (WIPO), green technology innovation (the total number of green invention patents and green utility model patents) was obtained from the website of the State Intellectual Property Office through python crawling (Xing et al., 2021; Shen et al., 2021). Socioeconomic data—GDP, industrial structure, population, urbanization rate, foreign direct investment, and technology investments—were extracted from the Hainan Statistical Yearbook (HNBS, 2011–2022), while environmental regulation was measured by pollution control investment from the China Environmental Statistical Yearbook (NBS & MEP, 2011–2022).

Data related to carbon sink were drawn from the China's multi-period land use land cover remote sensing monitoring data set (CNLUCC) published by the Chinese Academy of Sciences' Resources and Environmental Science Data Center (Xu et al., 2018). Urban green space data were supplemented from the China Environmental Statistical Yearbook (NBS & MEP, 2011–2022). Based on Fang et al. (2007) and Wei and Chen (2021), the carbon sink coefficients for various types of land use were as follows: cultivated land (42.2 t/km²), forest land (−64.4 t/km²), grassland (−2.1 t/km²), wetland (−25.3 t/km²), unutilized land (−0.5 t/km²), urban green land (−33.25 t/km², averaged from forest and grassland values). Fossil energy and heat-related carbon emission coefficients were obtained from Liu et al. (2015) and Gu et al. (2019), respectively. The share of non-fossil energy in power generation was derived from the China Electric Power Yearbook (CEC, 2011–2022), while thermal power emission coefficient was sourced from the Baseline Emission Factors for Regional Power Grids in China (MEE, 2010–2021). Detailed data sources and mathematical relationships between parameters are provided in Appendix A3.

Results

Validity testing. The SD simulation model abstracts the real world into an informational structure. Its quality depends on accurate real-world simulation. We used historical validation, stability check and sensitivity testing to evaluate its effectiveness.

- (1) Historical validation: We identified key parameters within the system and utilized the discrepancy coefficient to assess

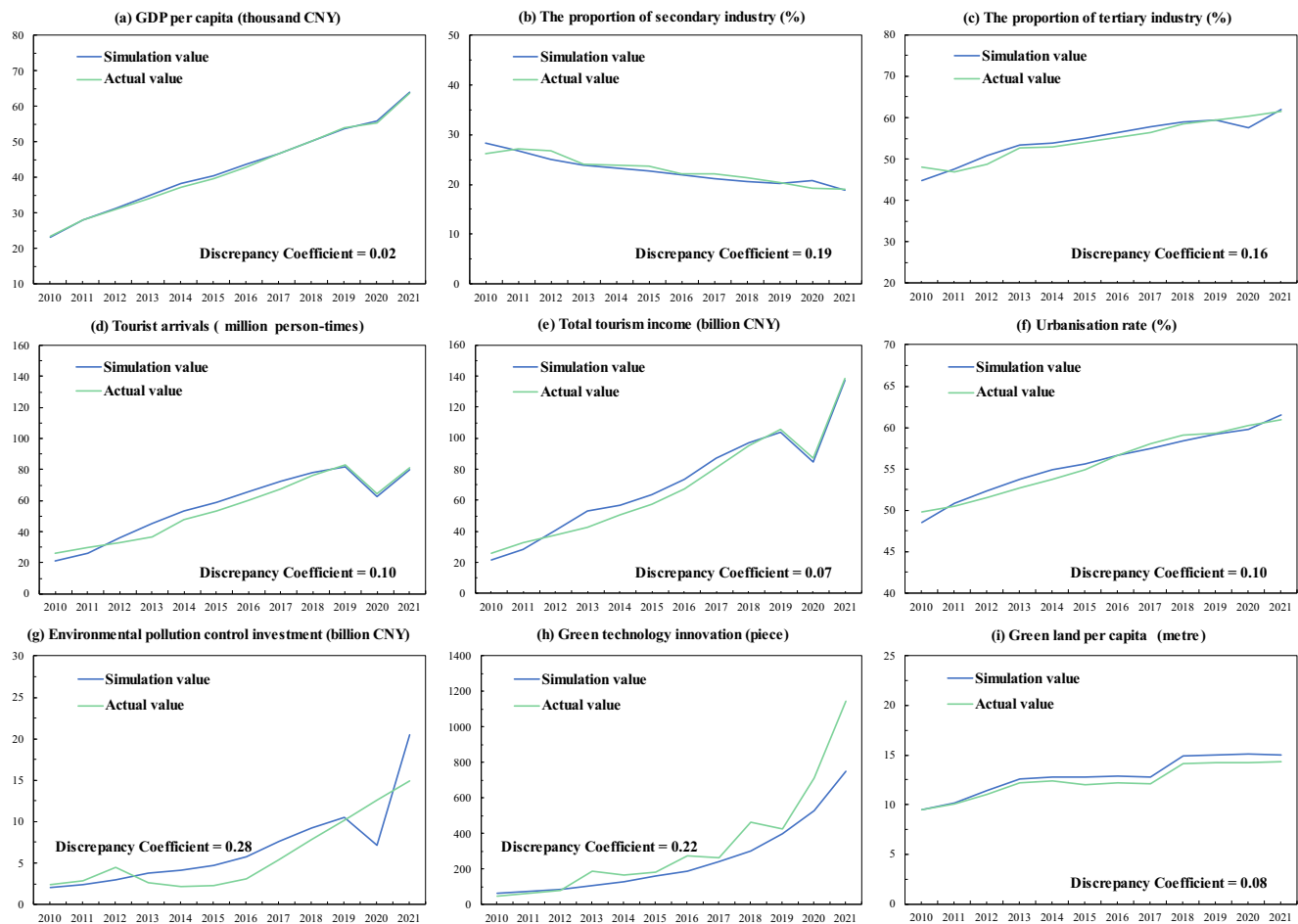


Fig. 8 Comparison of actual trends and simulated trends from 2010 to 2021. **a** (GDP per capita, 0.02 discrepancy), **b** (the proportion of secondary industry, 0.19), **c** (the proportion of tertiary industry, 0.16), **d** (tourist arrivals, 0.10), **e** (Total tourism income, 0.07), **f** (urbanisation rate, 0.10), **g** (environmental pollution control investment, 0.28), **h** (green technology innovation, 0.22) and **i** (green land per capita, 0.08) collectively demonstrate that the discrepancies between the simulated and actual values of key parameters are relatively small.

the differences between the simulation outcomes and historical data. As illustrated in Fig. 8, the discrepancy coefficients for the selected variables are all below 0.4, demonstrating that the model performs well and accurately mirrors real-world conditions (Barlas, 1989).

- (2) **Stability check:** We monitored the alterations in key variables by modifying the running step of the model to assess its stability. As illustrated in Fig. 9, it presents the variations of key variables spanning from 2010 to 2021 under diverse running steps, specifically 0.1, 0.25, 0.5, and 1 year. The outcome implies that the model did not generate excessive variability as a result of the length of the time interval. Thus, the model could be deemed relatively stable (Zhan et al., 2024).
- (3) **Sensitivity testing:** Sensitivity analysis examines the impact of parameter variations on model outputs. We selected 15 key parameters, incrementing each by 10% annually, and analyzed the sensitivity of five variables (each representing a subsystem) to these changes. As illustrated in Fig. 10, the sensitivity of the majority of parameters is below 0.1, indicating that the model is largely insensitive to parameter modifications, thereby affirming the robustness of the constructed model (Yang et al., 2019).

Historical trend results. Figure 11a indicates that Hainan is still far from achieving its carbon neutrality goals. Propelled by

tourism, Hainan's socio-economic development has quickened, leading to an increase in net carbon emissions from 27.37 Mt in 2010 to 43.40 Mt in 2021, with an average annual growth rate of 4.42%. This rise is primarily attributed to a continual increase in carbon emissions, which escalated from 28.48 Mt in 2010 to 44.49 Mt in 2021, at an average annual growth rate of 4.27%. Meanwhile, carbon sinks—which in this period included only land use carbon sinks, as Hainan's CCS projects were not yet operational—experienced a slight decline from 1.11 Mt in 2010 to 1.09 Mt in 2021, a reduction of approximately 1.23%. Nonetheless, Hainan has seen a declining trend in overall carbon intensity, with an average annual decrease of 5.88%.

Figure 11b shows that carbon emissions across all sectors display a fluctuating upward trend. Within this context, the production sector accounts for 87.72% of the region's total carbon emissions, a figure significantly higher than that of the residential sector. Within the production sector itself, emissions from the secondary and tertiary industries represent approximately 44.25% and 36.28% of total regional emissions, respectively. In the residential sector, coinciding with rapid urbanization, carbon emissions from urban residents not only exceed those from rural residents but also grow at a faster rate.

Figure 11c illustrates that the carbon intensities of various sectors display diverse trends. Specifically, the production sector's carbon intensity shows a declining trend, with the tertiary sector experiencing the most notable decrease (from 0.11 kg/CNY to 0.04 kg/CNY during the study period), gradually becoming

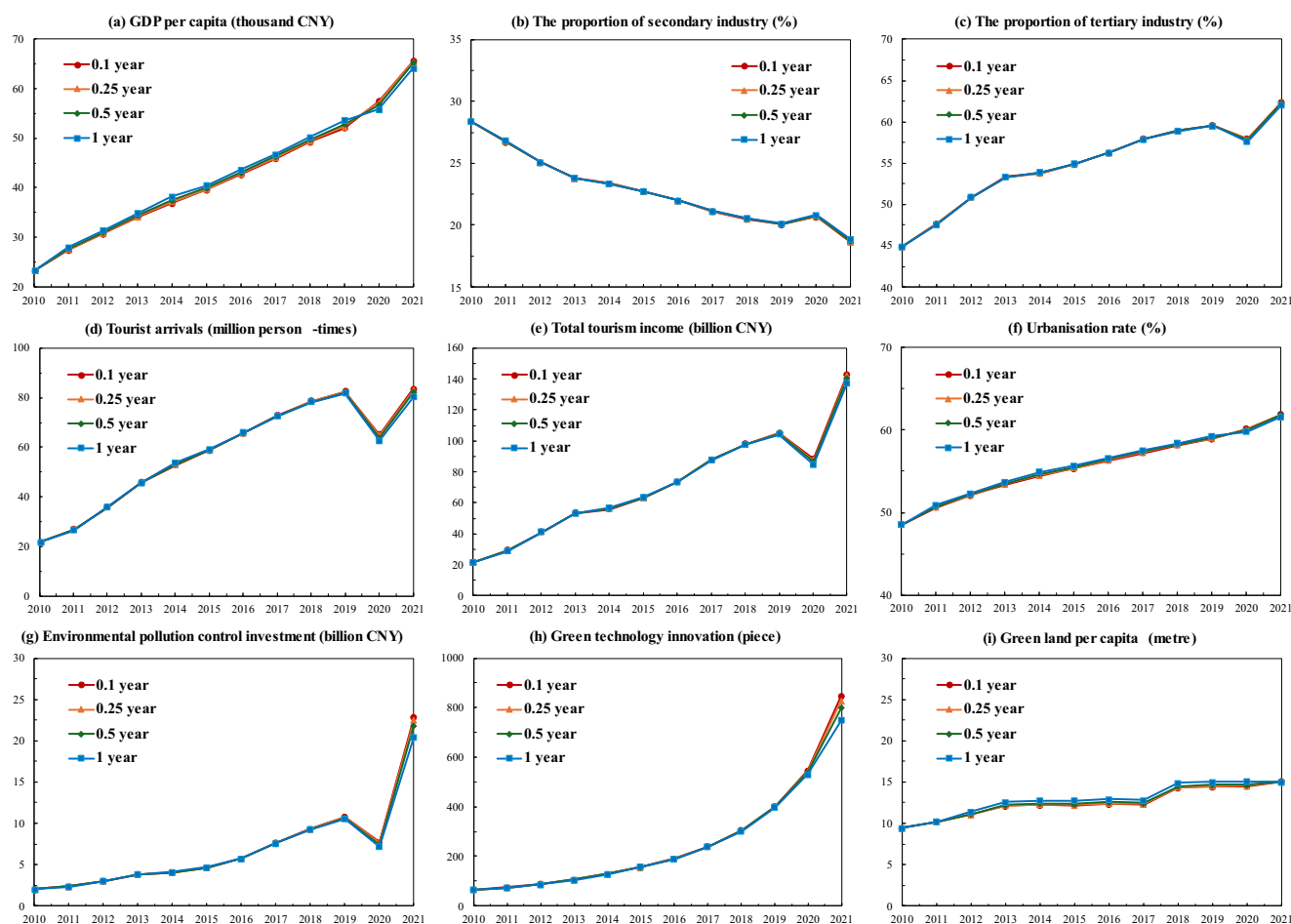


Fig. 9 Simulations are conducted with time steps of 0.1, 0.25, 0.5, and 1 year. **a** (GDP per capita), **b** (the proportion of secondary industry), **c** (the proportion of tertiary industry), **d** (tourist arrivals), **e** (total tourism income), **f** (urbanisation rate), **g** (environmental pollution control investment), **h** (green technology innovation), and **i** (green land per capita) all show that the curves within each panel match very closely, reflecting the good consistency of simulation results under different time steps.

comparable to the carbon intensity of the primary sector. In contrast, the secondary sector, as an energy-intensive industry, has a significantly higher carbon intensity compared to other sectors and has shown a slower rate of decrease. However, the per capita carbon emissions in the residential sector have been on a long-term upward trend, indicating that economic development and improved living standards stimulate residents to consume more energy for a higher quality of life.

Figure 11d demonstrates the carbon sequestration status of various land use types. Forestland remains the principal carbon sink, although its sequestration capacity subtly decreased from 1.41 Mt to 1.38 Mt throughout the study period. Urban green spaces and wetlands have experienced slight increases in carbon sequestration, thereby providing some supplementation to the destination's carbon sinks. Grasslands and unutilized lands contribute minimally, with very limited sequestration functions. Despite a consistent reduction in cultivated land area, which has led to a marginal decrease in carbon emissions, it continues to offset a significant portion of the carbon sequestration associated with land use.

Sensitivity analysis. This study used sensitivity analysis to explore the impact of tourism development on CNTDR. Therefore, we incorporated different levels of tourism development into the scenarios to analyze the sensitivity of the destination's net

carbon emissions and carbon intensity to varying levels. Specifically, using the historical trend as the baseline scenario, we simulated scenarios with tourist arrivals increasing and decreasing by 10%, 20%, and 30%, respectively.

Figure 12a, b illustrates that, during the study period, further expansion of the tourism industry increases net carbon emissions in the case area. Conversely, restricting tourism development decreases net carbon emissions. Therefore, from the perspective of absolute carbon reduction, tourism development appears to have a negative environmental effect on Hainan. According to the EKC theory, this may be because, as a developing region, continuous tourism development amplifies the scale effect, which predominates in this context (Ahmad et al., 2022b). In other words, at this stage of development, tourism growth fails to generate sufficient technological and structural advancements to offset the additional carbon emissions produced by economic growth.

However, given the significant economic and employment benefits generated by the tourism industry, it is necessary to discuss the relationship between emissions and value creation (Gössling et al., 2024). Therefore, we selected changes in carbon intensity as another critical reference indicator (Tong et al., 2022). Figure 12c, d shows that, compared to net carbon emissions, carbon intensity exhibits inverse changes in all scenarios. This means that by developing the tourism industry, the case area can support the implementation of low-carbon technologies and

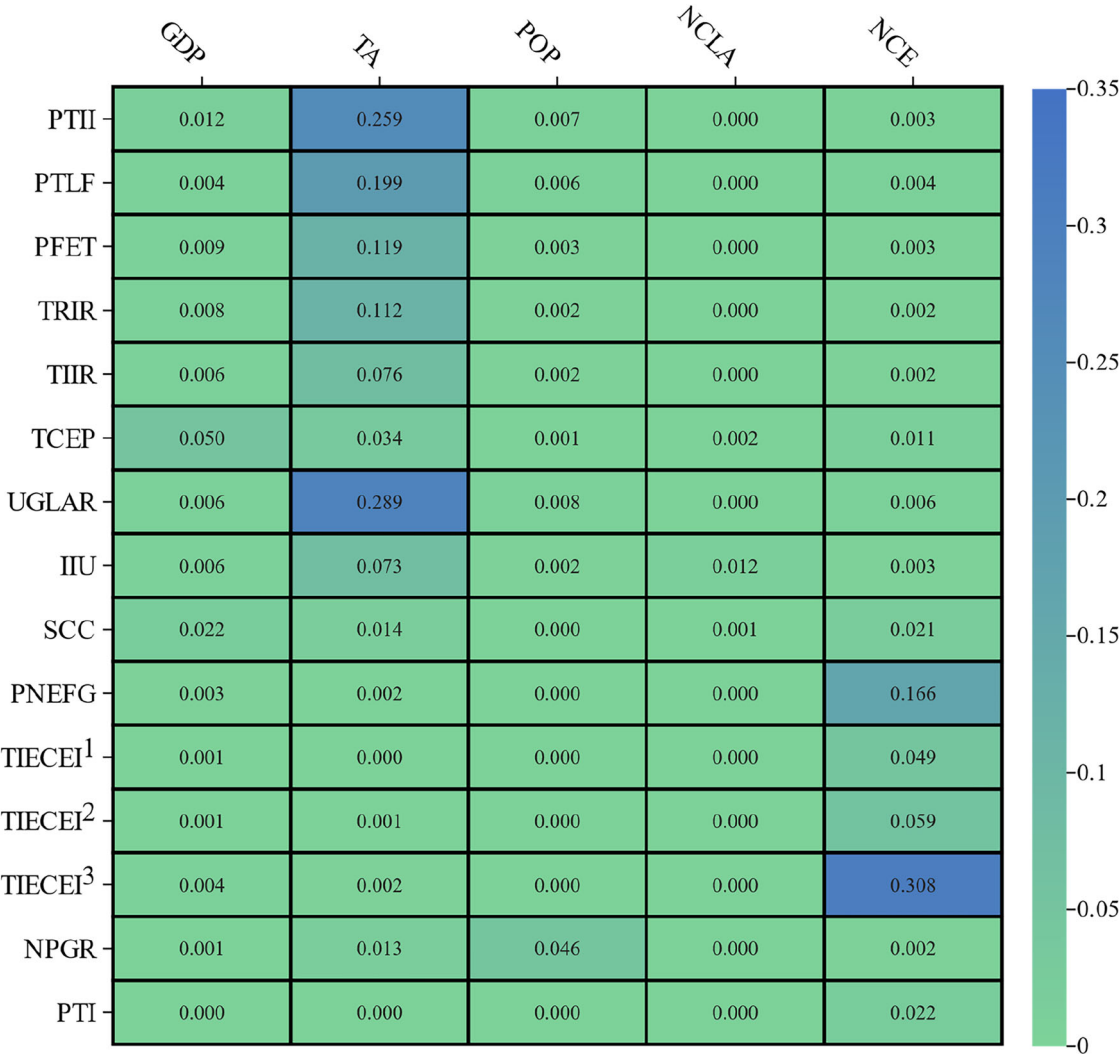


Fig. 10 Sensitivity analysis of the model to parameter changes.

sustainable practices, thereby reducing the carbon emissions per unit of economic output. This promotes economic growth while enhancing the region’s level of sustainable development.

Notably, besides identifying the direction of tourism’s environmental externalities, our findings suggest that, compared to traditional econometric models, the impact of tourism development on environmental performance appears to be less significant (i.e., the level of influence). According to the principles and methods of system dynamics, several reasons may explain this discrepancy: (1) CLD analysis suggests that tourism development exerts both promoting and inhibiting effects on regional net carbon emissions, with CNTDR arising from the interplay and offsetting of these effects. (2) SD establishes causal links among system factors through feedback chains, thus, the impact of tourism on regional carbon neutrality in this study is mediated by multiple feedback loops, rendering the influence indirect. (3) The SD model reveals how the accumulation and time lags of various factors influence the behavior of complex systems over time. In the pathway of tourism development’s impact on regional carbon neutrality, key factors such as GDP and population size are modeled as stocks within the SD model, indicating that tourism development has a cumulative effect on regional carbon neutrality. Consequently, in the short term, changes in tourism development levels are unlikely to significantly affect regional carbon neutrality.

Discussion

Theoretical implications. In destinations where tourism and the environment are interdependent, focusing on the environmental effects of tourism and the environmental management of destinations is of great significance for improving the environmental quality of these areas (Mihalič, 2013). We innovatively integrate LMDI decomposition with SD modeling to systematically analyze tourism’s multifaceted relationship with regional carbon neutrality, establishing a novel simulation framework for CNTDR. Therefore, this study advances existing research in the following ways.

Identifying potential key drivers. Understanding the determinants of regional carbon neutrality constitutes a prerequisite for establishing tourism’s role in destination decarbonization (Sun et al., 2022). Current scholarship predominantly employs critical factors based on theoretical background or empirical observation to explain variance in tourism-carbon neutrality relationships (Liu et al., 2022b; Erdoğan et al., 2022; Ehigiamusoe et al., 2023). While methodological advancements using EKC theory (Ahmad et al., 2022b) and IPAT model (Koçak et al., 2020) have improved factor selection for emission analyses, they remain insufficient in systematically revealing the constituent drivers within carbon neutrality subsystems. Thus, we introduce an extended-LMDI methodology that innovatively incorporates both carbon sources

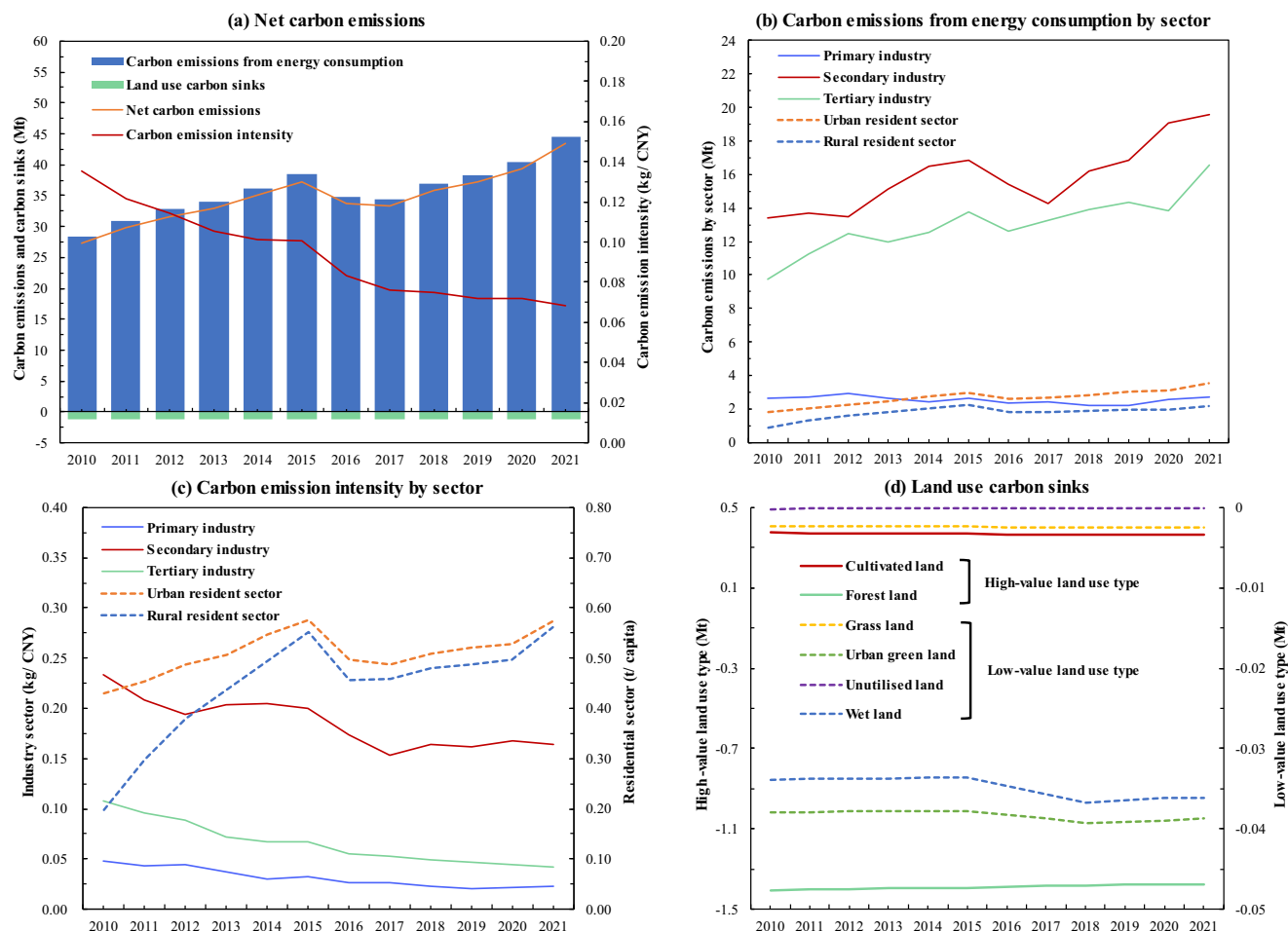


Fig. 11 Carbon neutrality simulation results for Hainan. Simulations focus on indicators related to carbon neutrality. **a** (Net carbon emissions) depicts the overall dynamics of carbon emissions and sinks. **b** (Carbon emissions from energy consumption by sector), **c** (carbon emission intensity by sector), and **d** (land use carbon sinks) further reveal developmental trends and structural characteristics within each sector.

and sinks, enabling granular identification of sector-specific drivers through decomposition of regional carbon neutrality into four components. This approach enhances the precision of driver identification across subsystems, thereby strengthening the theoretical framework for analyzing tourism's multi-dimensional impacts on carbon neutrality pathways.

Constructing feedback mechanisms to investigate the dynamics. Diverging from conventional factor decomposition approaches that quantify historical contributions of isolated variables, this study employs CLDs under the ECON-ESG framework to map systemic interactions between tourism development and carbon neutrality determinants. The analysis of mechanisms under this integrated approach has the following innovations: First, existing literature predominantly relies on singular metrics—such as tourism arrivals or tourism receipts—to assess tourism growth (Yildirim et al., 2021; Katircioglu et al., 2014; Liu et al., 2019). We integrate them in a unified framework and reveal how these indicators exhibit distinct pathways of influence on destination sustainability. Second, in addition to traditional macroeconomic factors analyses (Lee & Brahmasrene, 2013; Nepal et al., 2019; Zaman et al., 2017), we identify novel transmission mechanisms whereby tourism development influences regional net carbon emissions through residential sector and carbon sinks (land use and CCS) drivers—critical relationships underexplored in tourism environmental externality studies. Third, transcending linear perspectives, our mechanism analysis employs reinforcing and

balancing feedback loops to delineate tourism's dual environmental impacts, where externalities emerge from the interaction and accumulation of countervailing effects. For instance, tourism promotion could foster industrial upgrading to reduce industrial sector emissions while paradoxically accelerating construction land expansion and diminishing land use carbon sinks. This system perspective advances understanding of nonlinear tourism-carbon neutrality relationships.

Developing a quantitative analysis model. Current scholarship predominantly employs panel datasets to examine tourism-carbon emission relationships across global (Paramati et al., 2017; Shi et al., 2020), continental (Qureshi et al., 2017; Paramati et al., 2018; Khan et al., 2019), and regional scales (Chishti et al., 2020; Kumail et al., 2024). However, such cross-regional analyses risk oversimplifying spatial heterogeneity—particularly the systemic disparities in economic structures, institutional frameworks, technological capacities, and environmental governance between developed and developing economies (Koçak et al., 2020; Liu et al., 2022b). These contextual variations fundamentally alter tourism's environmental impacts across development stages, potentially generating misleading universal conclusions that neglect critical place-specific dynamics (Sun et al., 2022). We argue that single-region investigations offer superior analytical precision for exploring tourism externalities, enabling precise identification of tourism-environment interactions at defined developmental phases within geographically bounded systems.

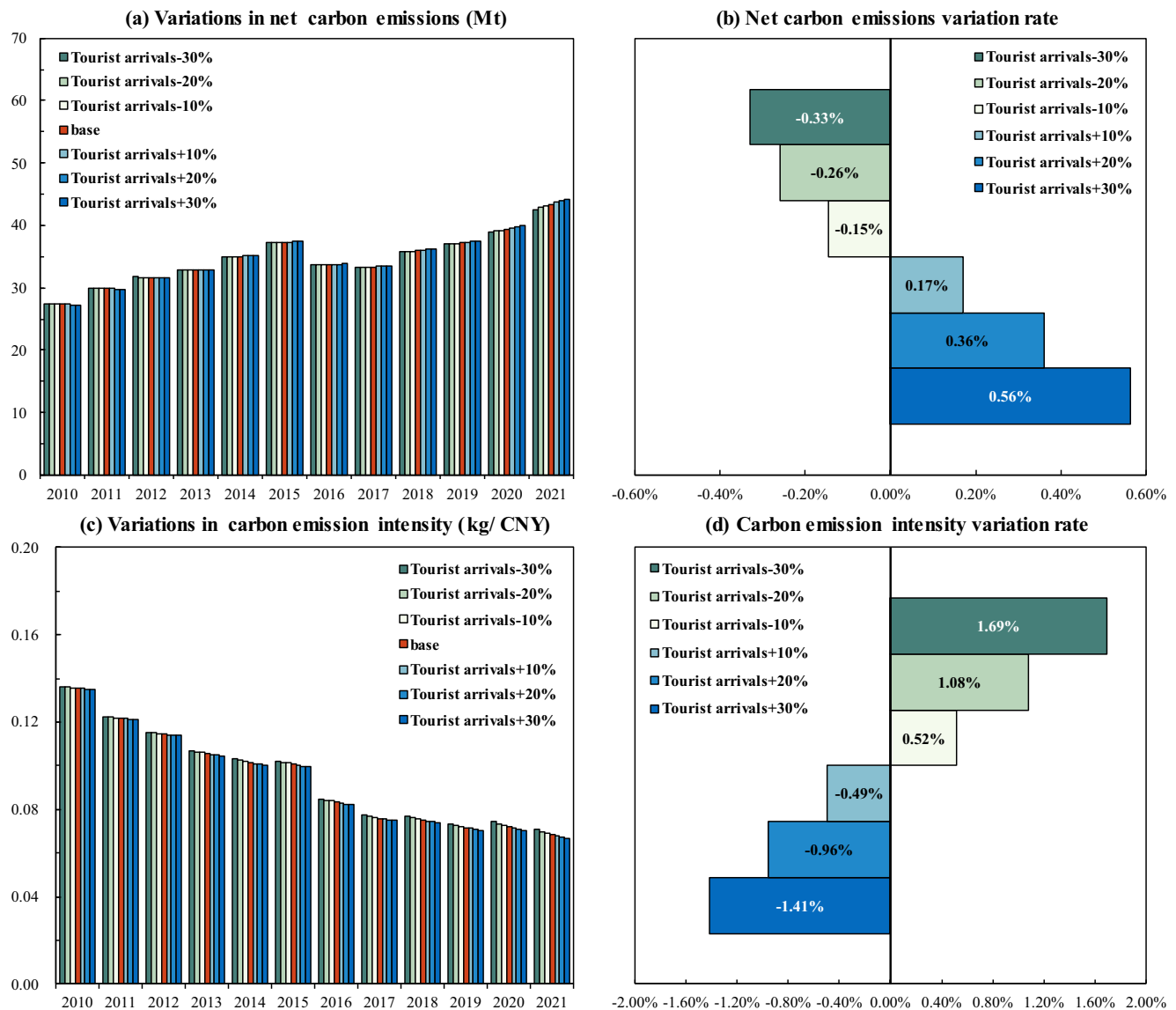


Fig. 12 Sensitivity analysis of tourism development. We adjust tourist arrivals with different variation ranges (-30%, -20%, -10%, base, +10%, +20%, +30%) to observe changes in core carbon neutrality indicators. **a** and **b** respectively represent the developmental trends and total variation ranges of net carbon emissions under scenarios of different variation ranges. **c** and **d** represent the developmental trends and total variation ranges of carbon emission intensity.

Yet current carbon neutrality modeling efforts remain disproportionately focused on major urban clusters (Luo et al., 2023; Zhan et al., 2024) and traditional industrial zones (Li et al., 2012; Guo et al., 2018), leaving tourism-dependent regions under-explored despite their unique sustainability challenges (Nepal et al., 2019). Addressing this gap, we pioneer a carbon-neutral development model specifically calibrated for tourism-reliant regions. This model can comprehensively reflect the development trends and characteristics of key indicators related to carbon neutrality in specific regions. Through parameter-informed sensitivity testing, the framework quantifies both direction and magnitude of tourism's environmental impacts across developmental stages. By integrating these functionalities, the model enables data-driven optimization of tourism-environment equilibria, providing destination planners with a robust tool to reconcile economic growth and ecological conservation.

Practical implications. Our SD model application to Hainan Island yields critical insights for climate governance in tourism-

dependent regions. The results reveal two overall trends: (1) As in many emerging economies (Mardani et al., 2019; Jiang et al., 2019), net carbon emissions grew steadily, driven by tourism-fueled economic expansion—a concerning trajectory given the climate vulnerability of island-based destinations. (2) Carbon intensity declined significantly, reflecting structural shifts toward service industries and incremental efficiency gains. This decoupling highlights tourism-dependent regions' potential to align development with global climate goals while enhancing long-term competitiveness. Notably, Hainan's carbon intensity remains below China's national average (Yang et al., 2021), underscoring tourism's inherent strengths as a low-carbon service sector. However, gaps persist compared to regions with well-developed service industries and high-quality development (Zhu et al., 2022; Luo et al., 2023; Shang et al., 2023b), emphasizing the need for systemic decarbonization strategies.

Sectoral disparities underscore the dual role of tourism in regional carbon dynamics. Productive emissions remain predominant, while the tertiary sector exhibits a marked reduction in

carbon intensity. This decline reflects tourism's capacity to drive structural transitions toward cleaner service-oriented economies. However, the secondary sector's sluggish decarbonization—attributed to persistent reliance on energy-intensive manufacturing—poses systemic risks. Without accelerated mitigation, industrial growth could negate tourism's efficiency gains, particularly in regions pursuing balanced industrial-service development. Thus, residential emissions continuously increased, driven by tourism-induced urbanization and rising living standards. This trend highlights the imperative to decouple prosperity from carbon-intensive consumption through targeted interventions.

Tourism development in Hainan has exerted divergent impacts on land-use patterns, revealing both ecological trade-offs and compensatory mechanisms. Despite stringent land conservation policies enacted since the establishment of the Hainan International Tourism Island, the rigid demand for construction land—driven by tourism-induced non-agricultural industrial expansion—has encroached upon ecological function areas. Forest coverage declined during the study period, somewhat compromising the natural carbon sequestration capacity of the area. Conversely, proactive policy interventions have partially mitigated these losses. Since the 2008 enactment and subsequent revisions of the Hainan Province Urban Landscaping and Greening Regulations (HPPG, 2024), urban green spaces have expanded as part of tourism-centric urban environmental improvement initiatives. Despite their limited sequestration efficiency, their incremental growth has partially offset the degradation of natural carbon sinks, highlighting the potential of policy-driven urban greening as a compensatory mechanism.

The sensitivity analysis underscores the dual role of tourism development in shaping regional carbon neutrality, offering critical insights for policymakers in tourism-dependent regions like Hainan. While the sector's expansion inevitably amplifies absolute emissions, the observed decline in carbon intensity signals tourism's potential to drive structural transitions toward service-oriented, resource-efficient economies. This paradox highlights the critical need for governance frameworks that strategically balance short-term developmental imperatives with long-term decarbonization goals. When sustainability is integrated into the core of tourism's value proposition, and governance frameworks align tourism growth with sustainable practices, prioritizing the tourism industry could effectively bring about environmental benefits.

Limitations. While this study provides an analytical framework for tourism-dependent regions aiming at carbon neutrality, four limitations warrant attention. First, the generalized approach may insufficiently capture destination-specific dynamics given substantial regional variations in tourism patterns and economic structures. Future research could prioritize comparative case studies, particularly examining how low-carbon ecotourism and cultural and heritage tourism influence regional decarbonization pathways. Second, although our SD modeling incorporates cross-sectoral drivers, the predetermined system boundaries necessitate broader incorporation of economic, social and policy factors to enhance practical applicability. Third, based on the availability of data, future research could conduct longitudinal analyses over a longer time span and at a finer temporal scale (e.g., seasonal/event-based fluctuations) to further deepen the dynamic understanding of this relationship. Lastly, future research could reduce analytical uncertainties by integrating field data from stakeholder interviews with probabilistic tools such as Monte Carlo simulations and Bayesian networks, complemented by multi-model validation frameworks.

Conclusions and policy implications

Concluding remarks. In recent years, the relationship between tourism and climate change has been a major area of concern. Against this backdrop, this paper constructs a quantitative analysis framework for carbon neutrality in tourism-dependent regions using systems thinking, studying it from both theoretical and practical perspectives. The main conclusions are as follows.

This study provides a novel elucidation of the intricate and dynamic interplay between tourism development and regional carbon emissions and carbon sinks. The tourism industry influences regional net carbon emissions through multiple pathways, including the driving factors of carbon emissions in industrial and residential sectors, and the driving factors of carbon sinks in land use and Carbon Capture and Storage. These pathways illustrate that tourism exerts both positive and negative effects on regional net carbon emissions, highlighting the dual nature of tourism's impact on environmental sustainability.

Based on logarithmic mean divisia index and system dynamics, this paper provides an interdisciplinary and systematic approach for carbon neutrality analysis and management in tourism-dependent regions. The empirical study, using Hainan as a case site, verifies the model's effectiveness. The model accurately reflects actual changes in carbon emissions and carbon sinks in Hainan. Sensitivity analysis empirically tests the role and status of tourism in destination environmental performance management.

The analytical framework and research methods proposed in this paper are not limited to Hainan but can be extended to other tourism-dependent regions. Future research can further optimize the model and enrich the analysis dimensions by integrating specific regional conditions. This approach can provide scientific evidence and support for carbon neutrality strategies in more destinations globally.

Policy implications. Based on our findings, we make the following policy recommendations:

- (1) Tourism-dependent regions should adopt cross-sectoral strategies to align industrial decarbonization with tourism development. First, governments could implement mandatory green certification systems for tourism-related industries and their supply chains to enforce sustainability standards. Second, circular economy principles could be integrated into tourism-driven waste management systems, creating closed-loop material flows across industrial sectors. Finally, industrial diversification efforts could prioritize high-value-added sectors, such as smart tourism equipment manufacturing. Meanwhile, regions could cultivate low-carbon tourism models, including eco-tourism, and cultural immersion experiences, thereby combining industrial growth with emissions reduction requirements.
- (2) Tourism-induced population dynamics require targeted residential policies. Urban planning should promote compact, mixed-use communities around tourism hubs to reduce transport-related emissions and be supported by affordable housing development near public transit nodes. In addition, governments can promote energy-efficiency certification of tourism transportation networks and lodging infrastructure while strategically deploying green technologies. Such interventions would not only drive the decarbonization of the entire industry, but also systematically scale up tourism-proven innovations into the wider community environment.
- (3) Tourism development could systematically strengthen natural carbon sinks through three interconnected mechanisms. First, establish binding ecological compensation policies that require tourism projects to invest in green

space enhancement, reforestation, and ecosystem restoration. Second, design certified ecotourism programs to engage visitors in conservation activities like maintaining green corridors or restoring wetlands, generating revenue for carbon sink maintenance. Third, impose a tourism-specific carbon levy to provide stable funding for emerging carbon removal technologies.

- (4) Rising uncertainties, such as those stemming from climate policy (Işık et al., 2025), climate change (Li et al., 2025), and economic policy (Işık et al., 2020), could affect destinations' sustainability efforts (Ongan et al., 2025). Thus, tourism-dependent regions must establish adaptive governance systems integrating continuous monitoring with coordinated responses. Key measures include establishing policy-responsive monitoring systems to track emerging climate regulations and assess their sectoral implications, and establishing flexible funding pools that reallocate resources as policy priorities and climatic conditions evolve. Additionally, multi-stakeholder policy dialogs should institutionalize iterative adjustments to decarbonization plans.

Data availability

The datasets generated during and/or analysed during the current study are described in the supplementary materials and are available from the corresponding author on reasonable request.

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HL: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing—original draft. YT: Conceptualization, Writing—review & editing, Supervision, Project administration, Funding acquisition.

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The authors declare no competing interests.

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Informed consent

This article does not contain any studies with human participants performed by any of the authors.

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