Research on Sustainable Tourism Development Path Based on Dynamic Regulation and Multi-Objective Optimization

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Abstract. The rapid development of the tourism industry brings economic benefits but also triggers environmental and social issues. This study addresses problems such as glacier retreat and ecological destruction caused by over-tourism, constructing a system dynamics model that integrates environment, economy, and society to comprehensively tackle key challenges in the tourism development of Juno City. The research employs various methods, including systems dynamics, nonlinear optimization, and sensitivity analysis, to quantify visitor numbers. This not only provides scientific and reliable decision-making support for Juno City's sustainable tourism development but also has significant potential for application and promotion, offering valuable insights for tourism development in other regions. The results indicate that seasonal visitor numbers should be dynamically regulated, adjusting investment structures through changes in environmental protection investments, community project investments, and tax rates to control visitor numbers and achieve sustainable tourism goals.

Keywords: Nonlinear Optimization, System Dynamics, Genetic Algorithm, Sustainable Development.

1. Introduction

With the global tourism boom, the tourism economy has become an important source of income in many regions. At the same time, the ecological and environmental problems caused by excessive tourism have become increasingly prominent, making the sustainable development of tourism a focus of attention for governments. Taking Juneau, Alaska, USA as an example, its unique glacier landscape is both a core resource to attract tourists and an important pillar of the local economy [1]. However, the rapidly growing number of tourists has caused hidden costs such as glacier retreat and ecological damage while bringing economic benefits, which makes it particularly important to explore a new model for the coordinated development of tourism and the environment. Despite the remarkable progress of existing studies, there are still three limitations of the existing results in the sustainable management of glacier tourist sites: first, traditional assessments mostly use static indicator systems [2], which are difficult to capture the dynamic feedback process of glacier ablation and tourist activities; second, existing regulation models tend to linearize the economic benefits and environmental costs [3], ignoring the glacier ecosystem's Finally, in view of the seasonal fluctuation of high-latitude tourism, there is a lack of a methodological framework that synergistically optimizes short-term regulation and long-term strategies. This has led to the “regulation lag effect” in practice - by the time environmental indicators issue an early warning, glacier degradation has already entered an irreversible stage [4].

Based on the system dynamics approach, this study constructs a sustainable tourism development model containing three subsystems: economic, environmental and social. First, the mechanism of the influence of the number of tourists on the economic index, resident satisfaction and environmental quality is quantified by establishing the causal feedback relationship between the subsystems. Then, using a nonlinear optimization algorithm, the dynamic responses of the three subsystems under different visitor control strategies were simulated and analyzed using the city of Juneau as an example. Due to the complex nonlinear relationship between system variables, this paper uses sensitivity analysis to identify key regulation parameters, including the proportion of environmental protection investment, community program inputs and tax rate adjustment. Finally, by comparing the comprehensive performance of the system under different regulation schemes, we propose a dynamic control scheme for the number of seasonal tourists in order to realize the balanced development of economic benefits and ecological protection. The results of the study show that by optimizing the investment structure and tax rate policy, the environmental pressure can be effectively reduced while guaranteeing the tourism income, which provides a scientific decision-making basis for the sustainable development of the city of Juneau and other similar tourist destinations.

2. The establishment of three subsystem models

2.1. Economic Subsystem

(1) Visitor Number Model

The economic subsystem model is based on tourist numbers N , tourism revenue R , tax rates T, and operating costs A [5]. This study related Juneau's visitor arrivals to the natural growth rate of visitors (Originated from website links: https://juneau.org/wp-content/uploads/2022/12/Juneau-Tourism-Survey-2022-Report-REV-12_1_22.pdf) and introduce a random variable ε, to build a dynamic model to represent fluctuations in visitor arrivals, so visitor numbers are expressed as:

$$N_t = N_{t-1}(1 + r_v + \varepsilon_t) \tag{1}$$

$$0 \le N \le N_{max} \tag{2}$$

$$N_{max} = min\{O_{physical}, O_{ecological}\} \tag{3}$$

A nonlinear model[6] is established, where N_t represents the number of visitors to Juneau,N_{t-1} represents the number of visitors received by Juneau in the previous year, r_v is the natural growth rate of the number of visitors obtained by data collection and processing, ε_t is a random variable representing the random fluctuation of the number of visitors. Among them, N_{max} represents the maximum number of tourists that Juneau can accommodate, $O_{physical}$ indicates the physical carrying capacity of Juneau, and $O_{ecological}$ represents the ecological carrying capacity of Juneau. Statistically, the number of visitors to Juneau is limited to 1.35 million per year, which has a good impact on the sustainability of the local environment.

(2) Income Model

Based on the number of tourists in Juneau, this study established an income model [7], statistically refined the expenses of tourists during their travel in Juneau, and established the following model in combination with local government tax policies and operating costs:

$$R = a_1 N + a_2 N + a_3 N + a_4 N - N(1 - T) - A \tag{4}$$

To quantify, this study defined a_1 as the cost of recreational activities in Juneau, a_2 as the cost of accommodation, a_3 as the cost of meals, and a_4 as the cost of local travel.It is known that tourists spend the most on travel, which is the main source of income, spend less on meals, and have relatively high operating costs[8].Meanwhile, taxes and fees contribute significantly to local conservation and construction.

2.2. Environment Subsystem

The environmental subsystem incorporates four key factors: glacier area St, air pollution index C, environmental protection investment W, environmental pressure F to establish a model.

(1) Glacier Retreat Rate Model

$$f = f_0 \cdot e^{x \cdot N} \tag{5}$$

In order to quantify the data, this study defined f_0 as the initial glacier retreat rate, x is the influence coefficient of the number of tourists on the retreat rate, it is apparent that the glacier retreat rate is affected by the number of tourists, The expression of glacier critical area is as follows:

$$\mathrm{S_t} \geq S_{critical} \tag{6}$$

Among them, critical $S_{critical}$ represents the critical area of glaciers. Based on the comprehensive data of glacier retreat rate [9] and retreat area, as well as the characteristics of Juneau City, the glacier area should be controlled at 1,000 square kilometers and must not fall below this limit.

(2) Environmental Stress Model

$$F = -k_1 \cdot N - k_2 \cdot C + k_3 \cdot R \tag{7}$$

Among them, F represents the pressure borne by the environment, k_1 is the coefficient of bearing the pressure of tourists, k_2 is the coefficient of influence of environmental pollutant emission, k_3 represents the efficiency of environmental protection technology. The maximum environmental bearing capacity expression is as follows:

$$\mathrm{F} \leq F_{max} \tag{8}$$

In the formula, F_{max} represents the maximum environmental carrying capacity. Considering the above three indicators comprehensively, the pressure on the environment should be less than 5,200,000.

2.3. Social Subsystem

This study mainly chose resident satisfaction E as the main consideration direction of social subsystem [10]. Resident satisfaction primarily depends on four factors: infrastructure load rate B, resident housing cost D, noise interference degree R and resident income level.

(1) Base Load Rate Variation Model

Resident satisfaction correlates significantly with the base load rate, and visitors will have a significant impact on the local base load rate. the model captures base load rate dynamics:

$$B_{t+1} = B_t + jN \tag{9}$$

Consequently, it has been observed that the temporal variable t represents the duration in years, while j denotes the coefficient of infrastructure load. It is ascertainable that there is a distinct correlation between the infrastructure load rate and the volume of tourists.

(2) Quality of Life of Residents:

Resident concerns primarily focus on infrastructure load rate, housing costs, noise disturbance, and income levels. To quantify satisfaction, the following model is established:

$$E = \beta_1 \frac{1}{B} + \beta_2 \frac{1}{D} + \beta_3 \frac{1}{R} + \beta_4 \frac{1}{V} \tag{10}$$

Among them, β_1, β_2, β_3 and β_4 are weight coefficients. It has been found that the degree to which residents are disturbed by noise is the main factor affecting their satisfaction. The income level of residents has the second greatest impact on their satisfaction, followed by the load rate of infrastructure, which has a relatively small impact. The cost of residents' housing has the least impact. The expression of residents' satisfaction is as follows:

$$\mathrm{E} \geq E_{min} \tag{11}$$

Among them, E_{min} represents the minimum satisfaction level of residents. The satisfaction of residents is mainly related to the load rate of infrastructure, the housing cost of residents, the pressure from noisy tourists and the income of residents. Among them, noise has the most obvious impact on the satisfaction of residents. The satisfaction of residents should always be higher than 0.7.

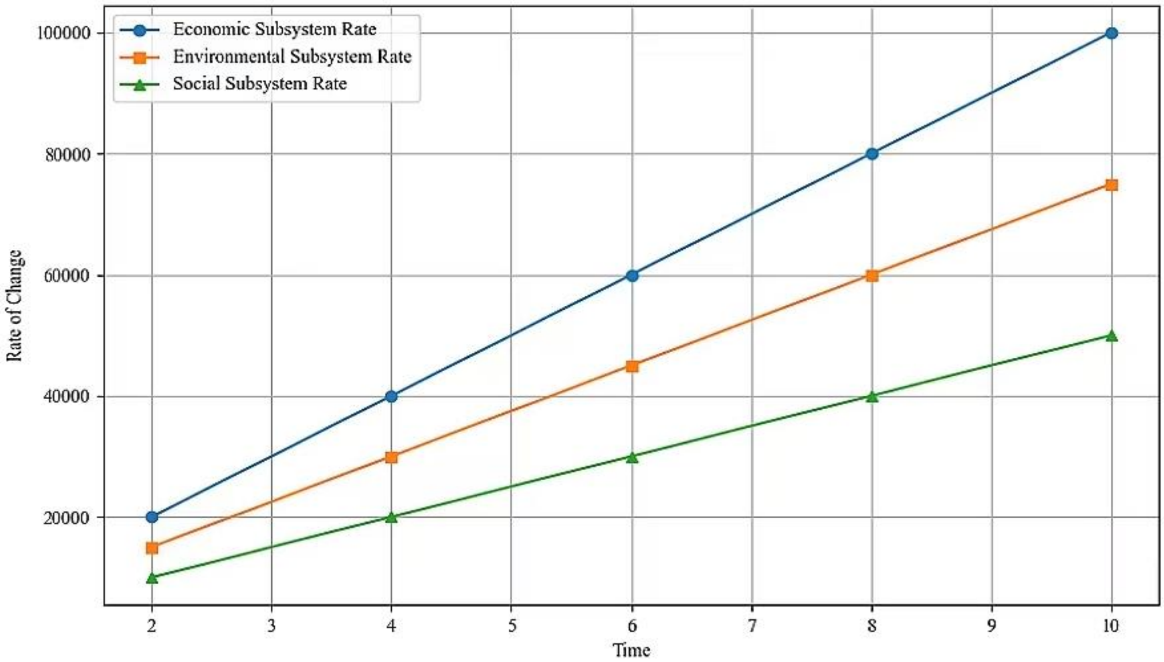

Figure 1. Rate of Change in Economic, Environmental, and Social Subsystems

It can be seen from the figure 1 that with the passage of years, the changes in the economic subsystem are increasing. The economy of Juneau City, Alaska, shows a trend of continuous development and progress. The development of tourism and the increase of tourists have promoted the economic progress of Juneau City. The compound annual growth rate of the economy can reach 50%, and the maximum change value can reach 100000. With the passage of years, the change rate of environmental subsystem also gradually becomes larger. With the change of years, more and more tourists come to Juneau, the impact on environment is increasing, and the damage degree of environment is more and more serious. The compound annual growth rate reaches 23.7%, and the highest change value reaches 76000. With the passage of years, the change of social subsystem is also higher and higher, the compound annual growth rate is about 25.1%, the highest value of change is close to 50000, the housing cost of residents is getting higher and higher, the interference degree of residents by tourists is constantly increasing, the load rate of infrastructure is constantly decreasing, and the satisfaction degree of residents is also constantly decreasing. Compared with the three subsystems, the change of economic subsystem is the most obvious, followed by environmental subsystem.

3. Objective Function

In the construction of sustainable tourism, the objective function should consider the income of Juneau, the area of Mendenhall Glacier and the satisfaction of residents. This study used nonlinear optimization methods to maximize Juneau City revenue, optimize glacier area, improve resident satisfaction, and maximize sustainable returns. The objective function expression is as follows:

$$U = R - (\lambda_1 \cdot \Delta S_t + \lambda_2 (1 - E)) \tag{12}$$

In the formula, U represents the maximization of sustainable income, R indicates the maximum income of Juneau City, S_t represents the optimal area of glaciers, λ_1, λ_2 is the proportion of environmental and social costs to income. To maximize the income of Juneau City, ensure income, promote government investment and maintenance in environmental protection, infrastructure, economic development and other aspects, achieve the optimal area of glaciers, slow down the retreat rate of Mendenhall Glacier, promote local ecological balance and the stability of the biosphere, increase residents' satisfaction, increase residents' income, reduce residents' housing costs, limit the volume of residential areas and streets, reduce noise interference to residents, flexibly adjust $\lambda 1$, λ_2

according to the actual situation, to achieve the maximization of sustainable income in the sustainable tourism model and promote development.

This study mainly carried out sensitivity analysis on the number of tourists, tax rate, environmental protection investment, infrastructure investment, community project investment, air pollution index, infrastructure load rate, residential housing cost, residents' income level, etc. Through Monte Carlo algorithm [11], based on random sampling numerical calculation, the sensitivity results are as follows Figure 2:

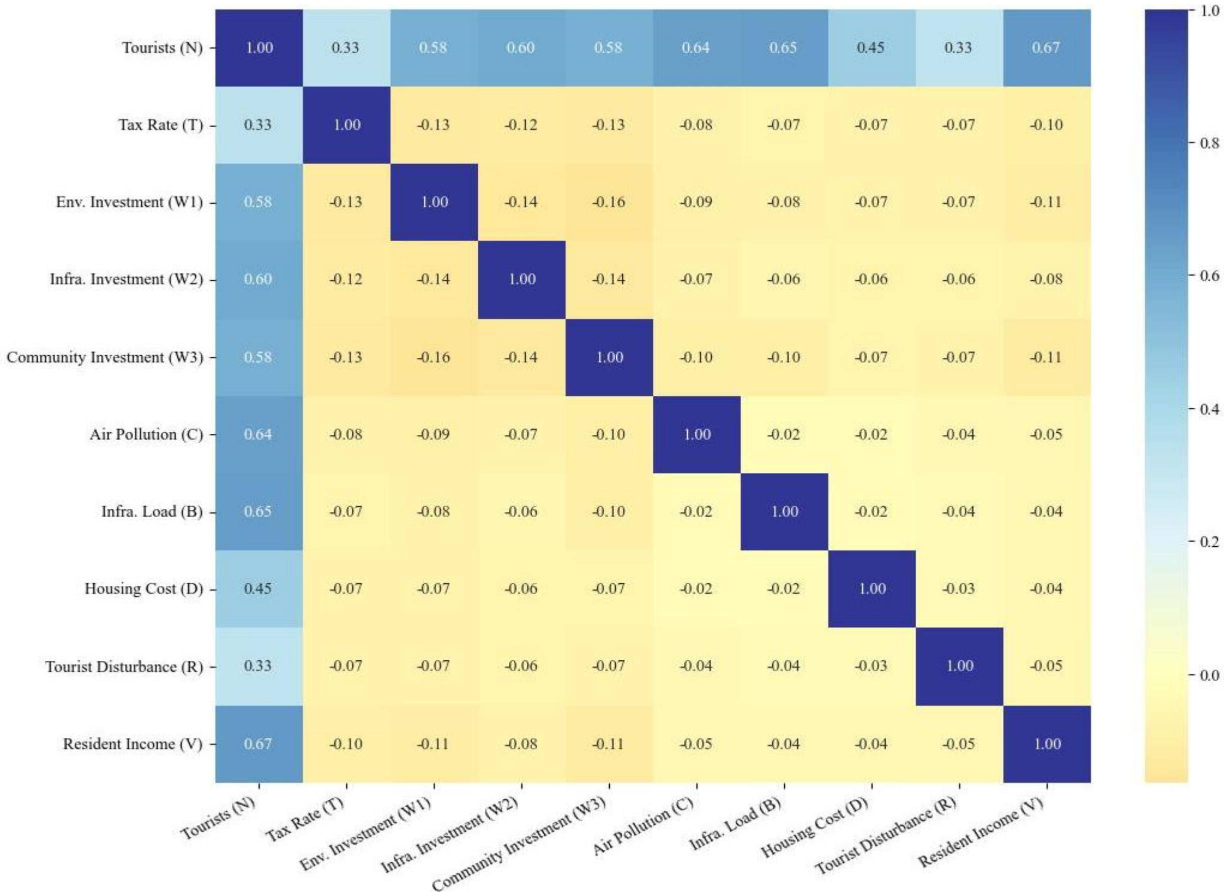

Figure 2. Interaction Sensitivity Analysis of Sustainable Income to Factors

It can be seen from the figure that for the establishment of sustainable tourism model, the most sensitive is the number of tourists, the sensitivity coefficient to sustainable income is 0.973, the sensitivity coefficient is high, and the impact on sustainable model is the highest; the sensitivity of tax rate to sustainable income is 0.086, and the impact degree is relatively low; the sensitivity of environmental protection investment to sustainable income is 0.107, which is more important than tax rate; The sensitivity of infrastructure investment to sustainable returns is 0.099, which has a smaller impact on sustainable returns; the sensitivity of community project investment to sustainable returns is 0.111, which is more important than infrastructure investment; the sensitivity of air pollution index to sustainable returns is 0.090, which has a minimal impact on sustainable returns; The sensitivity of infrastructure loading rate to sustainable returns is 0.088, which is basically equal to the impact of air pollution index on sustainable returns. The sensitivity of residential housing cost is 0.012, which is the least important to sustainable returns. The sensitivity of tourist disturbance is 0.034, which is more important to sustainable returns than air pollution index. The sensitivity of resident income level to sustainable returns is 0.033, which has little effect on sustainable returns, and the interaction among other variables is mostly low.

Table 1. Sensitivity Coefficient

High sensitivity factor		Medium sensitivity factor		Low sensitivity factor	
Number of visitors	0.973	Investment Community Programs	0.111	Infrastructure load factor	0.088
		Environmental Investments	0.107	Tax Rate	0.086
		Infrastructure Investment	0.099	Vistor Nuisance	0.034
		Air pollution index	0.090	Income level of residents	0.033
				Residents’housing costs	0.012

The table 1 shows the sensitivity coefficients of the influencing factors in the tourism system dynamics model, categorized according to high, medium and low levels. Among them, the number of tourists shows a very high sensitivity, indicating that it has the most significant impact on the system and is the core regulating variable in the model. Medium sensitivities include investment in community programs, environmental protection investment, and infrastructure investment, indicating that these variables have sizable regulatory potential for the system. In contrast, low sensitivity factors such as infrastructure loading coefficients, tax rates, tourist disruption, and resident income levels have a weaker impact on the system, with residential housing costs having the lowest sensitivity and can be prioritized less in policy design. The results of this analysis validate the key role of visitor management in sustainable tourism development, and provide a quantitative basis for resource allocation optimization - the need to focus on controlling the size of tourists and synergistically enhancing community and environmental protection investments to achieve balanced economic and environmental development [12].

4. Conclusion

This study addresses the issue of sustainable tourism development in Zhuluo City by constructing a nonlinear optimization model that integrates economic, environmental, and social subsystems. Using methods such as systems dynamics and genetic algorithms, it quantifies the impact of visitor numbers on glacier retreat, ecological balance, and resident satisfaction. The findings indicate that dynamically regulating visitor numbers, optimizing environmental investment, and structuring community project investments are key to achieving sustainable tourism. Based on the research findings, the report proposes the following actionable recommendations. First, implement a dynamic visitor number control mechanism to keep the annual tourist volume within 1.35 million, effectively alleviating environmental pressure while safeguarding economic benefits. Second, optimize the allocation of investment structures by prioritizing community livelihood projects and ecological environmental protection initiatives, aiming to enhance residents' life satisfaction and promote ecological sustainability. Finally, maintain policy flexibility. Given the relatively low sensitivity coefficients of taxation policies and infrastructure investments, it is recommended to adjust them flexibly as supplementary regulatory measures.

This paper provides a scientific decision-making tool for Juno City. By optimizing tourist capacity, adjusting investment structure, and implementing policy interventions, Juno City can achieve the dual goals of maximizing tourism revenue and minimizing environmental pressure. This model not only offers a scientific basis for decision-making in Juno City but also provides a replicable solution for other tourism cities facing similar challenges, further advancing the practice of global sustainable tourism development.

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