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Dynamic Analysis of Multi-dimensional Sustainable Development of Tourist Destinations Based on Dynamic System Modeling

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Abstract. In response to the problems of environmental degradation, social pressure and economic imbalance caused by excessive tourism in tourist destinations, this paper takes Juneau, Alaska, USA as the research object and constructs a multi-dimensional dynamic analysis model for sustainable tourism development based on dynamic system modeling technology. The number of tourists, the quality of life of residents, carbon emissions and infrastructure pressure were selected as the core indicators. By constructing the differential dynamic equations of each indicator, based on the actual data of Juno from 2014 to 2023 (such as 1.6 million tourists and 375 million US dollars in tourism revenue in 2023), the key parameters (positive feedback coefficient α=0.0723 for the number of tourists, negative feedback coefficient λ=-0.00503 for the quality of life of residents, etc.) were calibrated to quantify the coupling feedback relationship among the indicators. The results show that the model can effectively predict the dynamic trends of various indicators in the next ten years. The growth of the number of tourists has a significant positive driving effect on carbon emissions (γ=0.46314 t CO_2eq/tourists), and environmental protection expenditure can significantly suppress carbon emissions (δ=0.02647 t CO_2/US dollars). The Juno load threshold is the total infrastructure capacity K=3,358,064 units per year. This model provides quantitative tools and scientific basis for the dynamic regulation of the sustainable development of tourist destinations.

Keywords: Dynamic system modeling; Sustainable tourism; Multi-dimensional indicators; Parameter calibration; Tourism destination management.

1. Introduction

The rapid expansion of the global tourism industry has given rise to the phenomenon of "overtourism", and popular destinations are facing multiple imbalances in the environment, society and economy. Juneau, Alaska, USA, as a representative city of polar tourism, received 1.6 million cruise tourists in 2023, setting a new record high. While contributing 375 million US dollars to tourism revenue, it has also triggered a series of problems: the Mendengholl Glacier has retreated due to climate warming and the intensification of tourist activities, threatening the foundation of ecotourism. The infrastructure has been under high load for a long time, with road congestion and the crowding rate of public Spaces exceeding 60%. The quality of life index of residents dropped from 156.25 in 2021 to 152.15 in 2023, and the average annual growth rate of community protests was 15%. Traditional tourism management mostly relies on static data and experience-based decision-making, making it difficult to capture the dynamic coupling relationship among the number of tourists, environmental pressure, and social costs. There is an urgent need to reveal the feedback mechanisms of each factor through quantitative models to provide precise regulation solutions for sustainable development.

At present, the research on sustainable tourism development has formed a multi-dimensional evaluation system, but there are still limitations in terms of dynamics and coupling: First, most studies use static index weighting methods (such as entropy weighting - TOPSIS) to evaluate sustainability, ignoring the real-time feedback effect among indicators and being unable to predict long-term trends; Secondly, the quantification of key factors in the tourism system is insufficient. Existing models mostly simplify the linear relationship between the number of tourists and environmental pressure, without considering the moderating effects of variables such as infrastructure capacity and environmental protection expenditure. Thirdly, case studies mostly focus on urban destinations (such as Barcelona), while there are relatively few targeted models for polar natural tourism destinations (such as Juneau). These destinations have high ecological vulnerability and low infrastructure carrying thresholds, and thus require more precise dynamic parameter calibration. In conclusion, constructing a quantitative model that takes into account multi-dimensional coupling and dynamic feedback has become a key gap in addressing the sustainable development issues of polar tourism destinations.

This paper aims to construct a multi-dimensional dynamic system model suitable for polar tourism destinations. The specific goals include: (1) Identifying the core impact indicators for the sustainable development of Juno tourism (the number of tourists, the quality of life of residents, carbon emissions, and infrastructure pressure), and clarifying the dynamic evolution laws of each indicator; (2) Establish the differential dynamic equations of each index, and calibrate key parameters such as feedback coefficients and capacity thresholds based on actual data; (3) Quantify the coupling feedback relationship among the indicators and predict the changing trends of each indicator in the next ten years; (4) Provide a scientific basis for Juno to formulate sustainable tourism strategies such as tourist regulation, environmental protection investment, and infrastructure optimization.

2. Materials and Methods

2.1. Data source

The data of this study are all derived from public authoritative channels and official reports to ensure the scientificity and reliability of parameter calibration. The specific data types and sources are as follows:

(1) Core tourism data: Juneau's number of tourists (including the proportion of cruise tourists), tourism revenue, and tourism tax amount from 2014 to 2023 are derived from Juneau's 2023 Financial Report and statistics from the Alaska Tourism Bureau, of which the number of tourists in 2023 was 1.6 million and tourism tax revenue was US$3.202 million;

(2) Social and economic data: Residents 'Quality of Life Index (QLI), price level, housing vacancy rate, from Numbeo platform's 2021-2023 Juno Quality of Life Report. In 2023, the QLI is 152.15, and the price level index is 127.78;

(3) Environment and infrastructure data: The carbon emissions per capita of tourists refer to similar research in Barcelona (111.6 kg CO_2eq/day), and the infrastructure capacity data comes from LSC Transportation Consulting Company's "Juno Tourist Circulation Research Final Report". The average daily infrastructure capacity during the cruise season is 11039 people;

(4) Policy and expenditure data: Environmental protection expenditure, infrastructure improvement expenditure, estimated based on Juno's "Ocean Passenger Fee Plan" fiscal year 2024 data (US$21.459 million for environmental protection) and Spain's tourist tax allocation ratio (40% for environmental protection).

Data pretreatment: Remove abnormal epidemic data from 2020 to 2021, use linear interpolation to fill in a small number of missing values (missing rate $< 0.5\%$), standardize price levels, income and other indicators to ensure consistency in parameter calculation.

2.2. Research methods

This research takes dynamic system theory as the core and is carried out through a four-step process of "indicator identification-feedback relationship construction-parameter calibration-trend prediction". The specific method is as follows: First, core indicators are identified, combined with Juno's practical problems and literature review, and determined Four major indicators covering economic, social and environmental dimensions: The number of tourists (reflecting the scale of the tourism economy), residents 'quality of life (reflecting social impact), carbon emissions (reflecting environmental pressure), and infrastructure pressure (reflecting carrying capacity) ensure that indicators can fully represent the state of sustainable development. Secondly, build a dynamic feedback relationship between indicators, and design a dynamic relationship with positive and negative feedback mechanisms for each core indicator: changes in the number of tourists are positively driven by tourism revenue and negatively suppressed by infrastructure pressure. The higher the tourism revenue, the more attractive it will be to tourists. Strong, while overloading infrastructure will reduce the travel experience and thus reduce tourists; Changes in residents 'quality of life are positively regulated by housing supply and price levels. The more abundant the housing supply and the more stable the price, the higher the quality of life of residents. At the same time, due to the negative squeeze by the number of tourists, too many tourists will crowd out public resources and interfere with daily life; Changes in carbon emissions are positively driven by the number of tourists. Tourist activities (such as transportation and accommodation) will increase carbon emissions. At the same time, they are negatively alleviated by environmental protection expenditures, and investment in environmental protection. (such as low-carbon facility construction and ecological restoration) can reduce carbon emissions; changes in infrastructure pressure are positively superimposed by the number of tourists. The more tourists, the greater the demand for infrastructure. At the same time, due to the negative reduction of infrastructure improvement expenditures, infrastructure investment (such as road expansion and new public facilities) can improve carrying capacity. Then parameter calibration was carried out, and quantitative methods were used to determine the key parameters of each feedback relationship: for the income positive feedback coefficient of the number of tourists, the number of tourists from 2014 to 2023 was used as the dependent variable and tourism income as the independent variable, and calculated through linear regression to 0.0723, which represents the increase in the average daily number of tourists corresponding to every US dollar increase in tourism revenue; For the negative feedback coefficient of tourists on residents 'quality of life, based on the data of QLI and the number of tourists from 2021 to 2023, the linear relationship was fitted with the least squares method to get- 0.00503, which represents the decline in residents' quality of life index for every increase in the number of tourists; For the tourist positive coefficient of carbon emission, refer to the average daily carbon emission of Barcelona tourists and the average travel time of Juneau tourists.(4.15 days) Calculated to obtain 0.46314 t CO_2eq/tourist, which represents the average annual carbon emissions of each tourist; the negative carbon emission feedback coefficient for environmental protection expenditure, combined with the emission reduction efficiency of environmental protection expenditure in the literature and Juneau's actual situation, calibrated to obtain 0.02647 t CO_2/dollar, which represents the annual carbon emission reduction corresponding to each US dollar increase in environmental protection expenditure; For the total infrastructure capacity, combining the carrying data of the cruise season and the non-cruise season (209 days, with the capacity being 30% of the cruise season), 3358064 units/year was calculated, which characterized the annual maximum carrying capacity of Juneau's infrastructure; For the pressure relief coefficient for infrastructure improvement expenditures, it was determined to be 0.1 by referring to relevant literature and the actual effect of Juneau's infrastructure, which characterized the reduction in infrastructure pressure corresponding to each US dollar increase in infrastructure expenditures. Finally, trend prediction is carried out. Based on the calibrated dynamic feedback relationship, a numerical simulation method is used to predict each core indicator for ten years from 2024 to 2033, and the evolution trend of the indicator is presented through visual means, and the sustainable development status at different stages is analyzed.

3. Results

The sustainable tourism management model we developed for Juneau integrates models such as the dynamic system model and multi-objective optimization, and uses the entropy weight method to determine weights. This is to identify reasonable measures to address the economic, environmental, and social challenges posed by overtourism. The overall flowchart for building the model is shown in Figure 1.

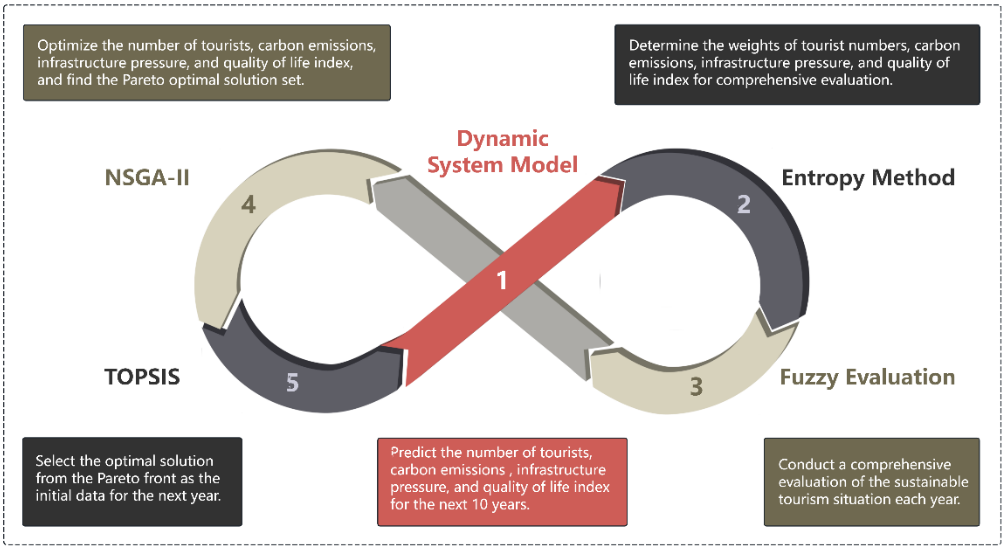

Figure 1. Overall flow chart for modeling

3.1. Dynamic formulas and parameters of the number of tourists

Changes in tourist arrivals V(t) are influenced by a number of factors, of which the attractiveness of economic returns and infrastructure pressures are the most significant drivers. Economic returns drive tourist arrivals by increasing the attractiveness of tourism, while infrastructure pressures inhibit tourist arrivals by degrading the tourist experience. The interaction of these two factors together determines the dynamics of tourist arrivals.

Based on the above analysis, we decide to express the dynamic equation of tourist volume as:

$$\frac{dV(t)}{dt} = \alpha \cdot R(t) - \beta \cdot I(t) \tag{1}$$

α is the positive feedback coefficient of income on the number of tourists, β is the negative feedback coefficient of infrastructure pressure on the number of tourists.

We use linear regression analysis to calculate the positive feedback coefficient α. In this problem, we take the number of tourists as the dependent variable (Y) and tourism revenue as the independent variable (X). We assume that there is a linear relationship between these two variables, where α is the slope (positive feedback coefficient):

$$Y = \alpha X + b \tag{2}$$

To calculate α, we need to use the following formula:

$$\alpha = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sum(X_i - \bar{X})^2} \tag{3}$$

Where X_i and Y_i are the values for each observation, and $\bar{X}$ and $\bar{Y}$ are the average of X and Y.

After the calculation, we get α = 0.0723.

3.2. Dynamic formulas and parameters of residents' quality of life

The study shows that an increase in the number of tourists negatively affects the quality of life of residents, while an improvement in the supply of housing and the price level can improve the quality of life of residents. Therefore, we decided to express the dynamic equation of residents' quality of life as [1]:

$$\frac{dQ(t)}{dt} = \frac{H(t)}{I(t) \cdot P(t)} - \lambda \cdot V(t) \tag{4}$$

Where $H(t)$ is the housing supply over time, $P(t)$ is the price level over time, and λ is the negative feedback coefficient of the number of tourists on the quality of life of the residents, which indicates the intensity of the negative impact of the number of tourists on the quality of life of the residents.

3.2.1. Calculation of weighted price indices P(t).

In 2023, the population of Juneau was 31,555. Based on the analysis of Juneau's consumption structure and the typical household expenditure ratio, the weights of food, housing, transportation, and other consumption are 0.2, 0.4, 0.15, and 0.25 respectively. According to the report data, we know the benchmark price, current price, price index, and weight of each category [2].The formula for calculating the weight-adjusted price index and the calculated results are as follows, where Ci denotes the price index of commodity group i and w_i denotes the weight of commodity group i:

$$P(t) = \sum(C_i \times w_i) \tag{5}$$

The value for food is 23.74, the value for Housing is 55.83, the value for Transportation is 18.71, and the value for Other is 29.50.

Sum the weighted price indices for each category to obtain the composite weighted price index:

P(t) = 127.78 That is, the current price level in Juneau P(t) is about 127.78.

3.2.2. Calculating the negative correlation index λ.

According to the data [3], in Juneau, the number of tourists was 1,300,000 with a quality - of - life index of 156.25 in 2021; the number of tourists reached 1,427,000 and the quality - of - life index was 154.90 in 2022; in 2023, the number of tourists was 1,600,000 and the quality - of - life index was 152.15.

There is a linear negative correlation between the Quality of Life Index (QLI) and the Tourist Number (TN). The model can be expressed as:

$$QLI = a \cdot TN + b \tag{6}$$

Where QLI is the quality of life index, TN is the number of tourists, a is the negative correlation index (λ).

Using least squares to calculate a and b, solve for a=-0.00503, b=7,308.12, and hence the negative correlation index λ = -0.00503.

3.3. Carbon Emission Dynamic Equation and Parameters

Surveys reveal a significant positive correlation between the number of tourists and carbon emissions, which can be effectively reduced by environmental protection expenditure. Thus, we express the carbon emission dynamic equation as:

$$\frac{dC(t)}{dt} = \gamma \cdot V(t) - \delta \cdot Eenv(t) \tag{7}$$

γ is the positive feedback coefficient of tourist numbers on carbon emissions, δ is the negative feedback coefficient of environmental protection expenditure on carbon emissions, and $Eenv(t)$ is the environmental protection expenditure.

3.3.1. Determination of the Positive Feedback Coefficient γ of Tourist Numbers on Carbon Emissions.

Studies indicate that the average carbon emission per tourist visiting Barcelona, Spain, is 111.6 $kgCO2eq/day$, with 95.6% of emissions coming from transportation, especially aviation [4]. Given that Juneau is also a coastal city primarily reliant on air and cruise travel, and lacking similar data for Juneau, we use this value to determine the γ value for Juneau's tourism.

The paper also states that an average holiday trip lasts 4.15 days. From this, we can infer the annual carbon emissions per tourist:

$$\gamma = 0.1116\ t\ CO2eq/day \times 4.15\ day = 0.46314\ t\ CO2eq/tourist \tag{8}$$

3.3.2. Determination of Time-Varying Environmental Protection Expenditure Eenv(t).

Spain allocates a portion of tourism taxes to environmental protection and infrastructure improvement, typically ranging from 30% to 50% [4]. Given the lack of data on Juneau's environmental expenditure, we assume that Juneau allocates 40% of tourism taxes to environmental protection.

Based on Juneau's 2023 financial report on tourism tax data [5] and the above assumptions, excluding the impact of the pandemic in 2020 and 2021, we calculated Table 1 and the fitting Figure 2.

Table 1. Juneau Tourism Tax Dollars and Environmental Protection Expenditures Dataset

Year	t	Tourist tax (dollar)	$E_{env}(t)$ (dollar)
2014	-9	1,303,919	521,568
2015	-8	1,378,365	551,346
2016	-7	1,489,743	595,897
2017	-6	1,488,951	595,580
2018	-5	1,497,843	599,137
2019	-4	1,632,106	652,842
2022	-1	2,583,590	1,033,436
2023	0	3,202,322	1,280,929

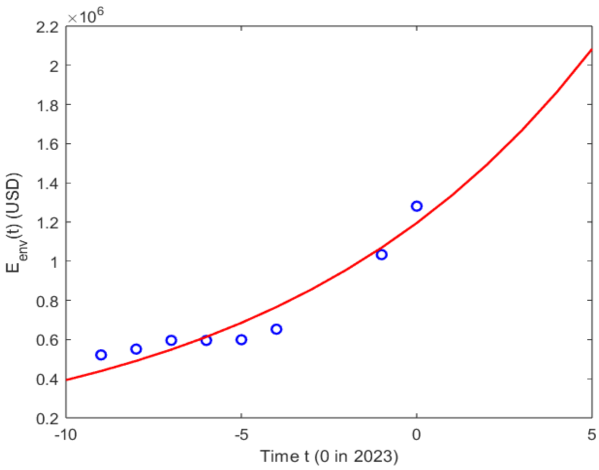

Figure 2. Exponential regression fitting of environ- mental protection expenditures

The relationship between Eenv(t) and time t is derived as:

$$Eenv(t) = 1280929 \times e^{0.111t} \tag{9}$$

However, we note that Juneau has a "Marine Passenger Fee Program," whose 2025 memorandum indicates that the number of tourists has remained stable in recent years, and the marine passenger fee revenue has also remained unchanged. These fees are all used for environmental protection expenditures, and the marine passenger fee revenue for the 2024 fiscal year was $21,459,000. Eenv(t) can be updated as:

$$Eenv(t) = 1280929 \times e^{0.111t} + 21459000 \tag{10}$$

3.3.3. Determination of the Negative Feedback Coefficient δ of Environmental Protection Expenditure on Carbon Emissions.

According to [6], a one-unit increase in environmental protection expenditure reduces greenhouse gas emissions by 2.08 units. Another study [7] indicates that a one-euro increase in environmental protection expenditure reduces per capita greenhouse gas emissions by 11.58 kilograms per year. Based on these two findings, we calculated and determined δ:

$$\delta = 0.02647\ t\ CO2/dollar \tag{11}$$

3.4. Dynamic Formula and Parameters for Infrastructure Pressure

Surveys show that an increase in the number of tourists significantly increases the pressure on infrastructure, which can be alleviated by infrastructure improvement expenditure. Therefore:

$$\frac{dI(t)}{dt} = \frac{V(t)}{K} - \eta \cdot Einfra(t) \tag{12}$$

K represents the maximum load of the infrastructure, η indicates the alleviating effect of infrastructure improvement measures on pressure, and $Einfra(t)$ is the infrastructure improvement expenditure.

3.4.1. Determination of Infrastructure Capacity K.

Based on the document [8], the cruise season typically lasts from May to September, about 129 days (short season) or 156 days (long season). The document provides the average daily cruise passenger capacity: C=11, 039 people, so the annual infrastructure capacity K_{annual}=11,039×156=1,722,084 passengers/year.

The annual infrastructure capacity is calculated using the following formula:

$$K_{annual} = K_{annual} \times \alpha \tag{13}$$

The infrastructure capacity coefficient α represents the infrastructure's ability to handle each passenger. It is known from the article that α=1.5, so K_{annual}=2,583,126 units/year.

During the non-cruise season ($T_{\text{non-cruise}}$=209 days), the infrastructure usage is lower. The capacity during the non-cruise season is 30% of the cruise season capacity, so the infrastructure capacity during the non-cruise season is $K_{\text{non-cruise}}$=774, 938 units/year.

K is the sum of the capacities during the cruise and non-cruise seasons, resulting in:

$$K = 3,358,064\ units/year \tag{14}$$

3.4.2. Determination of the Negative Feedback Index η.

According to the literature [9, 10], the negative feedback index η is 0.1.

3.5. Ten-Year Visualization Prediction of Four Key Indicators of the Dynamic System Model

Based on the aforementioned parameter settings, we have made a ten-year forecast for four key indicators of Juneau. Figure 3 visually presents the model's prediction results.

factor	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	total
Number of tourists(100000)	20.66	23.76	26.38	29.29	32.55	34.97	36.25	37.54	38.84	40.13	41.41	42.65	404.43
Carbon emissions (100000 tons)	7.782	8.576	9.405	10.27	11.17	12.11	12.78	13.09	13.22	12.95	12.75	12.46	136.563
Infrastructure pressure	6.34	6.35	6.362	6.376	6.392	6.411	6.432	6.456	6.482	6.512	6.544	6.526	77.183
Quality of Life Index	50.9	49.61	47.76	45.28	42.48	39.55	36.88	35.09	36.23	37.47	38.66	39.26	499.17

Figure 3. Ten-year projections for four key indicators of the dynamic systems model

4. Conclusion

Based on dynamic system modeling technology, this paper constructs a multi-dimensional sustainable development dynamic model of Juneau tourism destination, quantifies the coupling feedback relationship among tourist quantity, resident quality of life, carbon emission and infrastructure pressure, calibrates the key parameters such as tourist income positive feedback coefficient 0.0723, resident quality of life negative feedback coefficient- 0.00503, total infrastructure capacity 3358064 units /year, etc. It is predicted that the number of tourists and carbon emissions will increase first and then stabilize, the quality of life of residents will decrease first and then increase, and the pressure on infrastructure will increase steadily within ten years, which provides quantitative basis for sustainable tourism management in Juneau. The limitations of the study are that the model assumes a linear feedback relationship among indicators, without considering extreme weather, policy mutation and other sudden factors; in the future, nonlinear feedback mechanism can be introduced to optimize the model structure, integrate satellite glacier monitoring, real-time statistics of tourist flow and other data to improve the timeliness of parameters, and extend the model to other excessive tourism destinations such as Barcelona to form a universal dynamic regulation framework to help the implementation of global tourism sustainable development goals.

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