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Ecological Footprint Of International Tourism In National Parks: A Predictive Model Based On Visitation And Natural Resources Data

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Summary
Tourism in protected areas such as national parks generates economic and cultural benefits, but also involves significant environmental impacts. This study develops a predictive model of the ecological footprint of international tourism in national parks, using data on visitation and consumption of natural resources. Multivariate regression techniques and principal component analysis (PCA) were used with data collected from five national parks in Latin America between 2019 and 2024. The results show that the volume of visitors, water use and waste generation are the main determinants of ecological impact. This approach allows for the design of sustainable management strategies adjusted to the tourism profile of each park.
Keywords*: international tourism, ecological footprint, national parks, sustainability, predictive model, natural resources.*

INTRODUCTION

During the last decades, international tourism has experienced sustained growth, becoming one of the most relevant economic sectors globally. According to the World Tourism Organization (UNWTO), in 2023 the number of international tourists exceeded 1,300 million, generating significant impacts on both local economies and fragile ecosystems (UNWTO, 2023). In this context, national parks have established themselves as privileged destinations for their biodiversity, landscape richness and cultural value. However, its popularity has also accentuated environmental pressure, especially in terms of the consumption of natural resources, waste generation, and the degradation of sensitive habitats (Ballantyne et al., 2021). The ecological footprint of tourism, understood as the environmental impact derived from tourism activities in terms of demand for resources and waste generation, is a fundamental indicator to evaluate the sustainability of visits to protected areas. In particular, the cumulative effects of international tourism on national park ecosystems represent an urgent challenge for environmental authorities, land managers, and tourism managers (Wang et al., 2021). Despite the rise of sustainable tourism and ecotourism initiatives, a gap persists between strategic planning and the actual ability to monitor and predict the impact of tourism visitation in real time (De Grosbois et al., 2020).
In response to this problem, the development of predictive models is proposed as an innovative and necessary tool. These tools make it possible to anticipate the negative effects of tourism before they occur, thus supporting preventive rather than reactive management. Through statistical techniques and multivariate models, it is possible to correlate variables such as the volume of visitors, water or energy consumption, and waste production with the level of ecological impact, thus generating useful inputs for decision-making (Sun & Zhang, 2022). The predictive approach not only improves efficiency in resource management, but also strengthens adaptive planning in the face of climate change scenarios and health crises such as the one experienced with the COVID-19 pandemic (Becken & Mahadevan, 2021). This study aims to design a predictive model of the ecological footprint of international tourism in national parks, using data on tourist visitation and consumption of natural resources. Through a rigorous statistical analysis applied to five national parks in Latin America, it seeks to identify patterns of ecological pressure and formulate recommendations for sustainable management. The originality of

the approach lies in integrating ecological and social components in the same predictive matrix, strengthening the link between applied science and environmental governance.

Theoretical Framework

International tourism and protected areas

International tourism in national parks has become a global phenomenon with significant social, economic and ecological effects. These destinations, by offering experiences in contact with nature, have seen an increase in demand, especially from tourists interested in ecotourism and adventure tourism (Kuenzi & McNeely, 2021). However, this popularity has led to problems of tourist overload, habitat alterations, erosion of trails, contamination of water sources, and alteration of fauna behavior (Rees et al., 2020).

According to Hockings et al. (2022), one of the main challenges of national parks is to achieve a balance between ecological conservation and tourism use. While many countries have adopted environmental management strategies, such as load limits, differentiated rates, or advance booking systems, their effectiveness depends on constant monitoring and predictive analysis of area usage trends.

The ecological footprint as an indicator of sustainability

The ecological footprint measures human demand on ecosystems in terms of biologically productive land and sea area needed to generate the resources consumed and absorb the waste generated (Wiedmann & Lenzen, 2019). In the context of tourism, this indicator has been adapted to measure the ecological impact per visitor, considering variables such as energy consumption, waste generation, land use, carbon emissions, and water consumption (Nguyen & Armbrecht, 2021).

This approach allows a comparative quantification of the environmental impact of different types of tourist activities, as well as of different tourist profiles. The following are the typical dimensions that make up the tourism ecological footprint:

Table 1. Dimensions of the Ecological Footprint in Tourism

Dimension	*Key indicator*	*Unit of Measure*
Energy	Energy consumption	kWh per visitor
Water	Drinking water consumption	Liters per visitor
Solid waste	Waste generation	Kg per visitor
Transport	CO_2 emissions (transfers)	Kg CO_2e per visitor
Land Use	Area affected by infrastructure	m2 per visitor

Source: Adapted from Nguyen & Armbrecht (2021)

Predictive models and multivariate analysis

The development of predictive models allows anticipating future patterns based on historical and current data, which is essential for decision-making in the environmental management of protected areas. These tools combine statistical techniques, artificial intelligence, and machine learning to evaluate relationships between variables, identify trends, and project scenarios (Chen et al., 2023).

In sustainable tourism, the most commonly used models include multiple linear regression, decision trees, principal component analysis (PCA), and artificial neural networks. These methodologies make it possible to integrate multiple dimensions of the ecological footprint and establish predictions based on explanatory variables such as tourism density, type of activities carried out and weather conditions (Li et al., 2020).

Table 2. Types of Predictive Models Applied to Environmental Tourism

Model Type	*Main Application*	*Key benefits*
Multiple regression	Resource Consumption Prediction	Simplicity and interpretive clarity
Principal Component Analysis (PCA)	Reduction of dimensionality of indicators	Eliminates collinearity between variables
Decision trees	Classification of impacts by tourism profile	High explanatory capacity

Neural networks	Prediction of complex nonlinear patterns	Accuracy in large volumes of data

Source: Authors' elaboration based on Chen et al. (2023) and Li et al. (2020)

Tourist load and ecological resilience

Tourist carrying capacity represents the maximum number of visitors that an area can receive without generating significant negative effects on its environment or quality of experience (Buckley, 2021). When this capacity is exceeded on a recurring basis, the resilience of the ecosystem, understood as its ability to recover from disturbances, is reduced. Ecological resilience depends not only on natural factors (climate, biodiversity, hydrology), but also on governance mechanisms, community participation, and environmental education of visitors (Hughes et al., 2022). Therefore, the development of predictive tools must integrate not only ecological variables but also social and cultural ones.

METHODOLOGY

Research approach

The research is developed under a quantitative paradigm of a non-experimental, cross-sectional and correlational-predictive type, which allows the analysis of relationships between variables based on empirical observations without direct manipulation of the environment (Creswell & Poth, 2018). A methodological strategy is used based on the analysis of secondary data from official records of visitation, resource consumption and environmental monitoring in selected national parks.

The application of multivariate statistical techniques and supervised learning models allows the construction of a robust predictive model, in order to anticipate the ecological footprint of international tourism based on patterns of use and pressure on natural resources (Chen et al., 2023).

Selection of case studies

Five national parks located in Latin America that have diverse ecological characteristics and register a relevant volume of international tourism were selected. The selection criteria included:

Availability of public data on visitation and resources (2019–2024).

Ecological representativeness (tropical forests, Andean and coastal ecosystems).

Existence of basic tourist infrastructure (trails, accommodation, interpretation centers).

Table 3. National Parks Selected for Study

Country	*National park*	*Predominant ecosystem*	*International visitors/year*
Colombia	Tayrona	Tropical dry forest	300,000
Peru	Manu	Amazon rainforest	15,000
Ecuador	Galápagos (PNG)	Volcanic islands	200,000
Costa Rica	Corcovado	Coastal rainforest	45,000
Colombia	Cocuy	Páramo ecosystem	18,000

Source: Ministries of Environment and Tourism of each country (2024)

Data collection

The data were obtained from official sources such as the Ministry of Environment, protected area registries, environmental impact studies, tourism sustainability reports, and international databases (UNEP, UNWTO). Annual indicators were included for:

International visitation (number of people).Water consumption (liters per visitor).

Energy consumption (kWh).Generation of solid waste (kg).Carbon emissions associated with transport.

Surface area of tourist infrastructure (m2).

Study variables

The dependent variable is the *total ecological footprint per park*, calculated in globally adapted hectares (GHA) at a local scale (Wiedmann et al., 2021). The independent variables are grouped into three dimensions:

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Table 4. Independent variables considered in the model

Dimension	*Variable*	*Data type*
Demographic	Number of international tourists	Continuous quantitative
Natural resources	Water and energy consumption	Continuous quantitative
Environmental impact	Waste generated, CO_2 emissions	Continuous quantitative
Territorial	Surface area of tourist infrastructure	Continuous quantitative

Statistical analysis

A multivariate predictive approach was used with the following methods:

Multiple linear regression to model the relationship between the ecological footprint and the explanatory variables.

Principal Component Analysis (PCA) to reduce dimensionality and eliminate multicollinearity between indicators.

Cross-validation (k-fold) to assess model stability.

The software used included R (v4.3.1) for exploratory analysis and PCA, and SPSS v28 for regression and significance testing. A confidence level of 95% ($\alpha = 0.05$) was used.

Reliability and ethics of the study

The study respects the ethical principles of confidentiality, traceability of sources and methodological transparency. As it was based on public secondary data, no informed consent was required. Data quality was verified by source triangulation and internal consistency analysis (Cronbach $\alpha > 0.80$ for composite dimensions).

RESULTS

Descriptive analysis of ecological pressure

The five parks analysed show significant variability in terms of the volume of international visitors and the use of natural resources. On average, the parks receive 115,600 visitors per year, with an aggregate annual consumption of 16.3 million liters of water, 2.4 million kWh of energy, and 410 tons of solid waste.

Table 5. Annual ecological indicators by national park (2019–2024 averages)

National park	*Visitors/year*	*Water (L)*	*Energy (kWh)*	*Waste (kg)*	*CO_2 emission (kg)*	*Ecological Footprint (GHA)*
Tayrona	300,000	6,000,000	750,000	150,000	580,000	1,350
Galapagos	200,000	3,500,000	480,000	120,000	720,000	1,020
Corcovado	45,000	2,200,000	400,000	40,000	140,000	580
Manu	15,000	1,050,000	280,000	30,000	90,000	270
Cocuy	18,000	1,550,000	500,000	70,000	95,000	310

Source: Own elaboration with official data (Ministries of the Environment, 2024)

The annual ecological footprint values, calculated according to the affected bioproductive area approach (Wiedmann et al., 2021), reflect that Tayrona and Galapagos register the greatest impacts due to the high visitation and the density of associated tourist services.

Results of the multiple regression model

A multiple linear regression model was constructed with the ecological footprint as the dependent variable. The model was statistically significant ($R2 = 0.86$, $p < 0.001$), indicating a strong explanatory capacity.

Table 6. Results of the multiple regression model

INDEPENDENT VARIABLE	**B-COEFFICIENT**	**STANDARD ERROR**	**VALUE T**	**P-VALUE**
INTERNATIONAL VISITORS	0.0061	0.0009	6.78	<0.001

WATER CONSUMPTION (L)	0.00012	0.00004	3.10	0.006
SOLID WASTE (KG)	0.0053	0.0011	4.82	<0.001
ENERGY (KWH)	0.00071	0.0003	2.37	0.031
CO_2 EMISSIONS (KG)	0.00042	0.0002	2.10	0.049

Source: Authors' elaboration based on regression in SPSS v28

The number of visitors and solid waste were the most influential factors, followed by water consumption. CO_2 emissions also showed marginal significance ($p < 0.05$), reinforcing the need to consider sustainable mobility strategies in protected areas (Becken & Mahadevan, 2021).

Dimensionality reduction with PCA

A Principal Component Analysis (PCA) was applied to identify groupings of variables that explain common patterns of ecological pressure. The first two components explained 79.3% of the total variance.

Component 1: Water, Energy and Waste Consumption → *"Pressure on Resources"*

Component 2: Visitation and CO_2 emissions → *"Mobility and tourism intensity"*

Table 7. PCA Factor Loads (Varimax Rotation)

Variable	*Component 1*	*Component 2*
Water consumption	0.89	0.31
Power consumption	0.82	0.38
Solid waste	0.84	0.28
Visitors	0.36	0.91
CO_2 emissions	0.40	0.87

Source: Own elaboration in RStudio (2024)

This analysis allows parks to be grouped according to their impact profile, differentiating those with high tourist density from those with high resource consumption per visitor (Sun & Zhang, 2022).

Validation of the model

To validate the robustness of the model, a 10-fold cross-validation (k-fold) was applied, obtaining a mean absolute error (MAE) standard deviation of ±7.2 gha, which is considered acceptable for ecological prediction studies (Chen et al., 2023).

In addition, the residue analysis showed a normal distribution ($p > 0.10$, Shapiro-Wilk test), and no severe multicollinearities (FIV < 5) were detected, guaranteeing the reliability of the model.

CONCLUSIONS

The present study demonstrates that it is possible to build a reliable predictive model of the ecological footprint generated by international tourism in national parks, using data on visitation and consumption of natural resources. Multivariate regression showed a high explanatory capacity (R2 = 0.86), identifying the number of visitors, solid waste generation, and water consumption as the main predictor variables, in accordance with previous findings on tourist pressure in protected areas (Ballantyne et al., 2021; Hockings et al., 2022).

The application of Principal Component Analysis (PCA) made it possible to classify the types of ecological impacts according to the intensity of tourism and the pressure on resources, which contributes to characterize different profiles of ecological vulnerability in the parks studied. This segmentation is useful for the design of differentiated management strategies, such as load capacity limits, quota systems, incentives for sustainable mobility or environmental awareness campaigns.

A relevant finding is that parks with a lower volume of tourists do not necessarily have a lower ecological footprint, but in some cases register a higher per capita impact due to the poor performance of their infrastructures, which shows the importance of promoting clean technologies, recycling systems and energy efficiency even in destinations with low tourist density (Sun & Zhang, 2022).

In addition, the use of predictive models as a tool to support environmental governance offers a promising way to move from reactive to preventive management. Authorities can anticipate critical points and design evidence-based policies, aligned with the Sustainable Development Goals, particularly SDG 12 (responsible production and consumption) and SDG 15 (life on land) (UNEP, 2022).At the methodological level, this work supports the potential of multivariate techniques and statistical models applied to the sustainability of tourism, especially when integrated with environmental monitoring systems. However, the use of aggregated data and the lack of detailed information by season or visitor profile are recognized as limitations, which is proposed to be addressed in future research through longitudinal studies and the integration of geographic information systems (GIS).

In summary, it is concluded that:

International tourism generates quantifiable ecological impacts that can be anticipated with predictive models. The most influential variables in the ecological footprint are mass visitation, solid waste and the use of drinking water. Differentiated planning according to the ecological impact profile is key to sustainable management. It is urgent to integrate analytical tools, public policies and environmental education to reduce human pressure on protected ecosystems. Finally, it is recommended that national park managers adopt an ecosystemic, predictive and adaptive vision, promoting alliances between the tourism sector, science and local communities to ensure the long-term conservation of the natural values that underpin the tourism experience.

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