RESEARCH ARTICLE

Using simulation algorithm to evaluate the pressure and response of aging to urban ecological environment

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Population aging not only affects the social structure of cities but also has negative impacts on the ecological environment through resource consumption and environmental pollution. This research constructed a dynamic simulation model based on population aging levels and ecological pressure and analyzed changes in environmental pressure under different aging scenarios and their effects on ecosystems. The results showed that cities with high aging populations faced greater environmental pressures in terms of energy consumption and waste emissions, and as aging increased, the burden on ecosystems also increased. This study explored the potential application of intelligent ecological management models in alleviating the ecological pressures brought by population aging, proposing ecological restoration strategies at different levels of aging pressure, providing theoretical support for future sustainable urban development.

Keywords: population aging; urban aging; ecological environment; dynamic simulation model; intelligent ecological management.

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Introduction

The rapid development of global population aging has become a significant demographic shift, raising concerns about its multi-dimensional impacts on society, the economy, and the ecological environment. With the acceleration of urbanization, cities face increasing challenges associated with the growing elderly population. Aging leads to heightened resource consumption, greater environmental pressure in terms of energy use, waste emissions, and an increasing demand for green spaces. These changes create a complex relationship between aging populations and urban ecosystems, influencing both urban planning and environmental management strategies.

Currently, most research in this field has primarily focused on the economic and medical impacts of aging. However, limited attention has been given to how aging interacts with the ecological environment. Several studies have explored the relationship between urban green space and aging populations, focusing on the potential of green space to improve cognitive function, quality of life, and overall well-being. Studies have also explored how artificial intelligence and urban green infrastructure projects can be optimized to address the ecological pressures brought on by aging populations. Mohagheghi *et al*. summarized the problem of project portfolio selection and proposed how to select appropriate projects through effective decision models in the face of uncertainty [1]. Harrir and Sari analyzed the application of artificial intelligence in the supply chain and pointed out that AI technology could improve the efficiency of urban green infrastructure project management and optimize resource allocation [2]. Aydin *et al*. systematically reviewed the adaptive components in serious games and proposed that serious games had applications not only in the field of education [3]. Wang *et al*. conducted a biometric review of the application of rain gardens in urban environment, emphasizing the important role of rain gardens in storm water management and urban sustainability [4]. Further, Mofrad and Ignatieva reviewed the historical evolution of Canberra's green infrastructure and suggested that, with the process of urbanization, green infrastructure had gradually turned into an important environmental management tool [5]. Fernandez-Ballbe *et al*. reviewed the relationship between subjective aging and cognitive function, discussed the impact of green space on an aging society, and indicated that urban green space had the potential to improve cognitive function and quality of life of the elderly [6]. Paudel and States studied the ecological services and ecological burden of urban green space and found that, compared with lawns, flower grassland played an outstanding role in enhancing biodiversity and provided better ecological services [7]. In addition, Li *et al*. reviewed the progress of biological age research and suggested the impact of ecological environment, social factors, and health management on human biological age, providing a new perspective for urban greening research [8]. Goldman and Sterner discussed the relationship between environment and epigenetics and proposed the regulatory role of natural environment on human aging process, providing a theoretical basis for the construction of urban green infrastructure [9]. Pitt *et al*. studied the impact of urban form on the health outcomes of children and adolescents and found that urban green space had a positive impact on the health of young people in particular, emphasizing the significance of the design and layout of green space in urban planning for public health [10]. Semeraro *et al*. proposed that, in urban green space planning, emphasis should be placed on the comprehensive consideration of ecological functions and social benefits, emphasizing the synergistic effect of health, human welfare, and environmental protection [11]. Further, Teater and Chonody reviewed how elderly people define successful aging and proposed the role of green space in an aging society [12], while Foo *et al*. discussed a variety of aging assessment methods, emphasizing the importance of urban green space in promoting physical and mental health and delaying aging [13]. Despite progress in understanding the effects of aging on urban environments, there remains a significant gap in research regarding the specific mechanisms through which population aging affects ecological systems. The need for integrated dynamic models that quantify these impacts and provide actionable solutions is urgent. The impact of aging on resource consumption, pollution, and green space demands requires urgent attention to support sustainable urban development.

This research analyzed the pressure and response mechanisms of population aging in urban ecological environments to establish a quantitative assessment model based on a simulation algorithm to better understand the interactive relationship between aging and the environment, which would allow for the identification of key factors that affected the stability and service capacity of urban ecosystems. A dynamic simulation model was developed to assess the ecological pressures associated with aging populations by integrating data on urban aging and ecological environment indicators such as resource consumption, pollution emissions, and green space demand. By optimizing the parameters and validating the model, the dynamic effects of aging on the environment under different scenarios were evaluated. The findings of this study provided crucial insights into the risks that aging posed to urban ecological environments and offered evidence-based recommendations for managing these risks. The study's results contributed to the broader field of urban planning and environmental management and offered scientific guidance for decision-makers. By promoting the coordinated development of ecological protection and population structure adjustments, this research supported the goal of achieving sustainable urban development in the face of global demographic shifts.

Materials and methods

Data collection and sample selection

(1) Sources of urban aging data

Population aging data were selected as social variables and were obtained from the National Bureau of Statistics of China (http://www.stats.gov.cn), local statistical yearbooks, and annual reports publicly released by relevant government departments. The dataset from National Bureau of Statistics included national-level aging data such as the proportion of the elderly population, the old-age dependency ratio, and the average life expectancy. The local statistical yearbooks contained city-specific aging data including elderly population proportions and retirement rates, which were published by local statistics offices across various provinces and cities, and the specific yearbooks for each city could be accessed through their respective local government portals. The annual reports from government departments covered data on population aging indicators such as the proportion of the retired population obtained from publicly available annual reports issued by relevant governmental bodies. These reports were typically available on the respective governmental department's official websites. All data was from 2012 to 2022. The core data used in this study included the proportion of the elderly population, the old-age dependency ratio, the average life expectancy, and the proportion of the retired population. These datasets were chosen based on completeness, accuracy, and consistency of the time series.

(2) Selection of indicators related to ecological environment

The ecological environment variables used in this study were selected from three categories including resource consumption, pollution emission, and ecological service functions. These indicators were derived from environmental monitoring departments, public environmental reports, and satellite remote sensing data. The resource consumption was the total urban energy consumption being measured in terms of "ten thousand tons of standard coal" and tracked annually for each city. The environmental pollution included the total solid waste emissions, which were measured in "ten thousand tons," and calculated annually for both industrial and domestic waste. The ecological function referred to the green coverage per unit area and was expressed as a percentage. It was derived from remote sensing data and updated annually. Environmental quality included the air quality index (AQI) that was used to reflect the overall air quality with dimensionless values obtained from environmental monitoring data. Water quality was the surface water quality standard compliance rate and expressed as a percentage, which indicated how much of the water body met national standards with monitoring data on water bodies. These indicators were collected regularly and represented dynamic changes in the urban ecological environment over time. Data processing and standardization were carried out to ensure consistency and comparability across the different cities.

(3) Data multiprocessing and standardization

To ensure the applicability of the data in the model, comprehensive pre-processing and standardization were carried out. The missing values of the time series data were completed, and the linear interpolation method was used to fill in a small number of missing values, while the data samples with high missing rates were eliminated. All variables were uniformly converted, and quantitative indicators such as energy consumption and waste emissions were standardized into intensity values per square kilometer to enhance comparability [14]. The minimum-maximum normalization method was used to convert all variable values into the interval between 0 and 1 to avoid the unbalanced influence of different dimensions on the model operation. To eliminate the possible multidisciplinary problem, the correlation coefficient matrix between variables was calculated, and the variables with correlation higher than 0.8 were eliminated, so that the input variables of the model were independent. After the pre-processing was completed, the data was stratified random sampling and divided according to the ratio of training set and test set as 8:2 to provide high-quality data input for model training and verification.

Model construction

(1) Simulation algorithm selection and theoretical basis

Dynamic system model was selected as the core simulation algorithm to evaluate the pressure and response mechanism of aging on urban ecological environment. The dynamic system model was suitable for dealing with complex systems with multi-variable interaction and capturing the dynamic change process in time series data. The model assumed that ecosystem stress came from age-related variables, and the response included changes in environmental quality and adjustments in resource use efficiency [15]. The cumulative effect of aging variables on ecological environmental pressure was shown as follows.

$$P(t) = \alpha_1 \cdot O(t) + \alpha_2 \cdot R(t) + \epsilon \quad (1)$$

where *P(t)* was the total pressure value of the ecological environment. *O(t)* was the dynamic change of the proportion of the elderly population. *R(t)* was the proportion of the retired population. α_1 and α_2 were the coefficients. ϵ was the random disturbance term.

(2) Model architecture design and hypothesis

The design of model architecture was based on the logical framework of input-intermediate process-output. The input layer included age-related variables including old-age dependency ratio and average life expectancy, and eco-environmental variables such as total energy consumption and air quality index. In the intermediate process, dynamic equations were used to simulate the accumulation and effect of aging variables on ecological environment pressure. The output layer generated pressure response relationship data for verification and analysis. The hypothesis was set as that the influence of aging variables on ecological pressure had a nonlinear relationship, and the marginal contribution to environmental pressure increased with the increase of the proportion of elderly population after a certain threshold; the response of the ecosystem had a lag effect, and the impact of resource consumption and pollution emissions on environmental quality was delayed; the ecosystem could partially recover the cumulative effect of stress with the intervention of environmental governance.

Algorithm implementation and parameter optimization

The model implementation was based on Python (https://www.python.org), and the dynamic system simulation library was used to write and run the algorithm. The parameter optimization was completed by gradient descent method to minimize the error between the output pressure value of the model and the actual data. The optimization process was based on cross-validation method, which divided the data into a training set and a verification set and gradually adjusts the parameter values.

Implementation of pressure response analysis model

Based on dynamic system output, the pressure response analysis model constructed the functional relationship between ecological environment pressure and system response including environmental quality change and resource consumption pattern adjustment. The description of the impact of environmental pressure on the ecosystem was shown below.

$$R(t) = \beta_1 \cdot P(t) + \beta_2 \cdot Q(t) + \delta \quad (2)$$

where *R(t)* was the ecosystem response value. *P(t)* was the total pressure value. *Q(t)* was the resource utilization efficiency. β_1 and β_2 were the coefficient of δ as environmental impact factors. The parameter values were determined by stepwise regression method. The verification results showed that the pressure response function could describe the dynamic relationship between environmental pressure and ecosystem response and provide a quantitative basis for optimization strategy. The final model output was the predicted value of response under different pressure levels, providing data support for subsequent path recommendations.

Urban sample distribution and experimental scene setting

The research selected 30 representative cities as samples and categorized them into high, medium, and low aging pressure groups based on their aging levels, ecological environment conditions, and economic development characteristics, which covered regions in eastern, central, and western China with Shanghai, Beijing, Guangzhou, Tianjin, Shenzhen, Hangzhou, Suzhou, Chengdu, Zhengzhou, Harbin as high aging pressure group; Wuhan, Chengdu, Nanjing, Xi'an, Chongqing, Dongguan, Shijiazhuang, Hefei, Fuzhou, Jinan as medium aging pressure group; and Guiyang, Urumqi, Nanchang, Yinchuan, Lanzhou, Hohhot, Urumqi, Baotou, Yantai as low aging pressure group. These cities were chosen based on their aging levels, ecological environment conditions, and economic development characteristics, which were extracted from annual statistical data and monitoring reports from 2012 to 2022. The scenario analysis methods were employed to evaluate three intervention scenarios including no intervention scenario that was assumed that the aging level and ecosystem were not subject to external control, observing the changes in pressure under natural conditions; mild intervention scenario that was assumed that limited resources were optimally allocated, green coverage increased, and waste emissions decreased; comprehensive intervention scenario that simulated the implementation of systematic environmental management measures.

Simulating operation and verifying indicators

The simulation run was based on a dynamic system model. After the experimental scenario was input into the model, time series data was generated, and variables such as environmental pressure value, resource utilization efficiency, and ecological restoration index were output. The applicability and accuracy of the model were evaluated by the model validation indexes including root mean square error (RMSE), mean absolute error (MAE), and coefficient of determination (R^2). These indicators were used to quantify the degree of deviation and fitting effect between model output and actual data. The RMSE was calculated as below.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2} \quad (3)$$

where Y_i was the observed value. $\hat{Y}_i$ was the model prediction. *n* was the sample size. During the verification process, 30 cities were divided into a training set for model parameter optimization and a test set for evaluating the generalization ability and prediction accuracy of the model. The model should accurately reflect the dynamic impact of aging pressure on the ecosystem under different scenarios and provide a basis for subsequent policy recommendations.

Results and discussion

Basic characteristics of aging data in different cities

The basic characteristics of aging data in different cities demonstrated significant variation. The average proportion of the elderly population constituted 18.5% of the total population with a standard deviation (SD) of 5.2% and a range from 12.1% to 31.4%, indicating considerable variation between cities. Similarly, the elderly dependency ratio showed an average of 24.7% with a SD of 6.8%, showing substantial diversity across

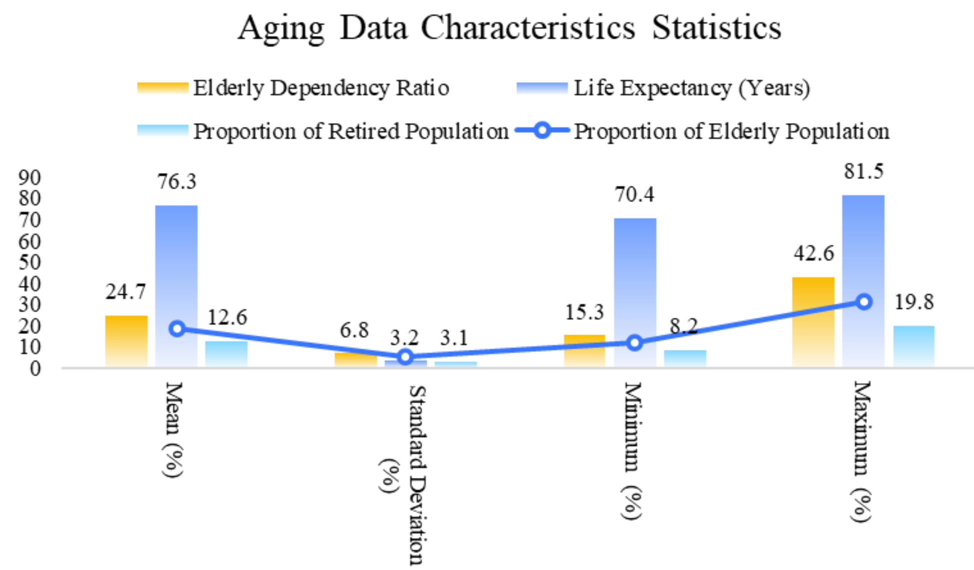

Figure 1. Characteristic statistics of aging data.

Table 1. Parameter setting and optimization process.

Parameter name	Initial value	Adjustment step	Optimized value	Description
α_1	0.5	0.01	0.78	Impact coefficient of elderly population proportion on pressure
α_2	0.3	0.005	0.42	Impact coefficient of retired population proportion on pressure
ò	0.1	0.001	0.05	Range of random disturbance fluctuations
Threshold Parameter	20	2	26	Turning point for non-linear environmental pressure changes

regions. The average life expectancy of the elderly population was 76.3 years with a SD of 3.2 years, suggesting relative consistency in life expectancy across the cities. The average proportion of the retired population was 12.6% with a SD of 3.1%, showing less variability compared to the other indicators. These findings highlighted the diversity of aging characteristics and their potential impact on ecological pressures (Figure 1).

Parameter optimization process and results

The model parameters were optimized using a gradient descent method. The impact coefficient of the elderly population proportion on ecological pressure was optimized from an initial value of 0.5 to 0.78 with a step size of 0.01. The impact coefficient of the retired population proportion was adjusted from 0.3 to 0.42 with a step size of 0.005. The range of random disturbance fluctuations was reduced from 0.1 to 0.05 with an adjustment step of 0.001. The threshold parameter for non-linear environmental pressure changes was optimized from 20 to 26 with an adjustment step of 2 (Table 1). The optimization results showed that these adjustments significantly improved the model's accuracy in predicting ecological pressures.

Data analysis results

Cities with different aging levels showed significant differences in ecological environmental pressure. As cities with high aging pressure (elderly population ratio ≥ 20%) had higher energy consumption, waste emission, and green coverage, their resource utilization efficiency and environmental quality indicators were poor. In contrast, cities with medium aging

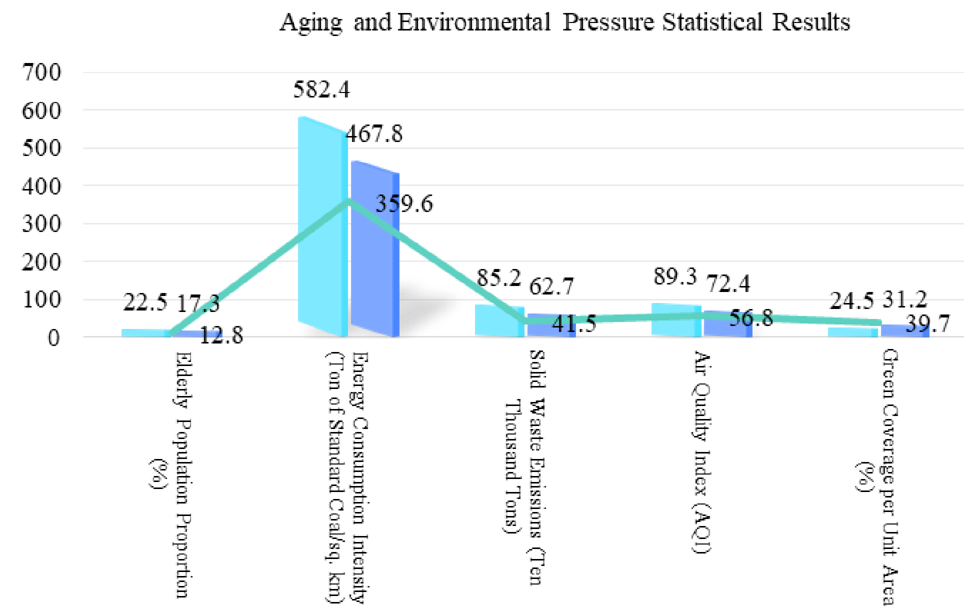

Figure 2. Statistical results of aging and environmental stress.

pressure (elderly population ratio between 15% and 20%) experienced moderate ecological pressure with their environmental governance measures insufficient to optimize resource allocation and benefits. Cities with low aging pressure (elderly population ratio < 15%) exhibited more stable ecological performance, though future ecological pressures might increase as aging levels rise (Figure 2).

Suggestions

(1) Urban ecological restoration

The core of urban ecological restoration strategy was to optimize the allocation of natural resources and improve environmental quality to achieve sustainable development of ecosystem. Based on the simulation results, cities with high aging pressure should give priority to increase urban green coverage, vegetation restoration, and ecological corridor construction to improve environmental carrying capacity, strengthen the treatment of pollutants, establish a strict waste classification and recycling system for the management of industrial waste and domestic waste. For cities under moderate aging pressure, it was suggested to implement regional governance strategies, increase investment resources in ecologically fragile areas, and achieve land rehabilitation and water quality improvement. Cities with low aging pressure should pay attention to the forward-looking environmental protection, formulate long-term plans, and prevent possible ecological degradation risks in the future. Ecological restoration and urban renewal were carried out simultaneously, so that the results of ecological restoration could be integrated into the improvement of urban functions.

(2) Ease the ecological pressure of aging

The path to alleviate the ecological pressure of aging should be promoted from the micro-economic and technical levels. By optimizing the allocation of public resources, especially the layout of medical and elderly care facilities, reducing the concentrated impact of aging on urban resource consumption, improving energy efficiency, and promoting the use of clean energy to slow down the rising trend of energy consumption caused by aging, the elderly population should be encouraged to participate in community ecological governance and environmental protection activities, and a social regulation mechanism for aging pressure should

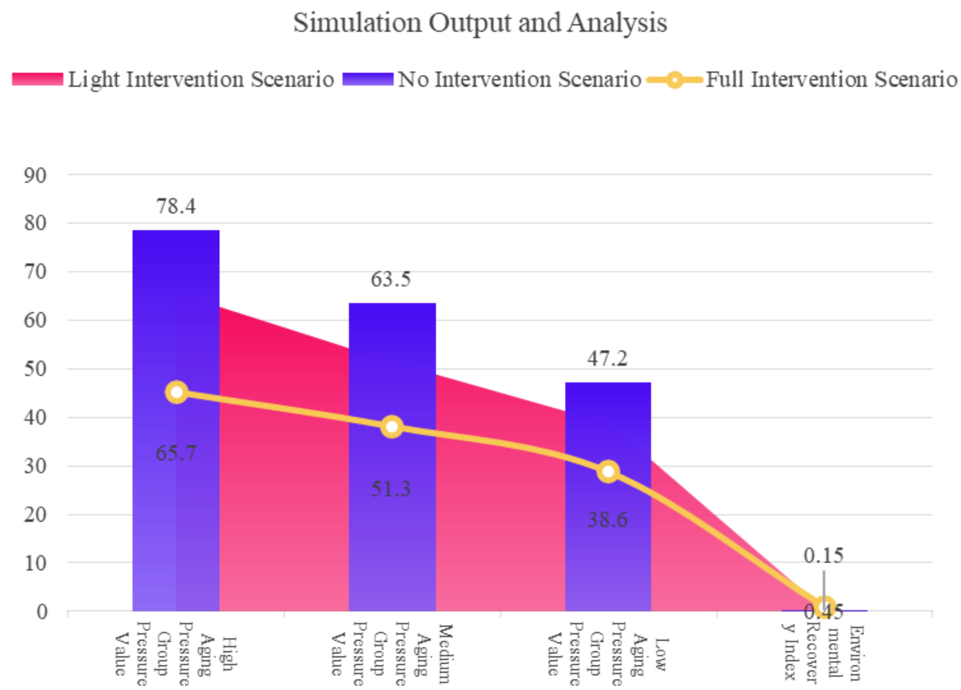

Figure 3. Simulation run output and analysis.

be formed. In small and medium-sized cities, green industries and sustainable agriculture should be developed to alleviate the high pressure of traditional industries on the environment. At the technical application level, distributed energy systems and intelligent power management technologies were promoted to reduce the intensity of energy consumption per unit area of the city.

(3) Intelligent ecological management mode

The intelligent ecological management model was based on information technology and big data analysis to provide dynamic and accurate solutions for urban ecological governance. Cot technology monitored air quality, water quality, and energy use in real time to build a dynamic database of the urban ecological environment. The machine learning algorithms and predictive models were combined to identify potential risk points in the ecosystem ahead of time and develop targeted interventions. In cities with a high degree of aging, the intelligent management model could optimize the efficiency of resource allocation and reduce the high demand pressure of the elderly population for ecological services by establishing an ecological information platform for the public, making environmental data transparent, and forming an eco-friendly lifestyle for residents. The collaborative operation of the intelligent management platform enabled accurate control of resource consumption and real-time tracking of ecosystem restoration, ensuring scientific and timely ecological management decisions.

Simulation algorithm results

Under different intervention scenarios, the influence of aging on the ecological environment exhibited nonlinear characteristics. In the no-intervention scenario, cities with high aging pressure experienced higher ecological stress than cities in other groups. In the comprehensive intervention scenario, the ecological stress of all cities decreased, showing the potential benefits of environmental governance. The results of the mild intervention scenario were in between, emphasizing the importance of governance measures in alleviating ecological pressure (Figure 3).

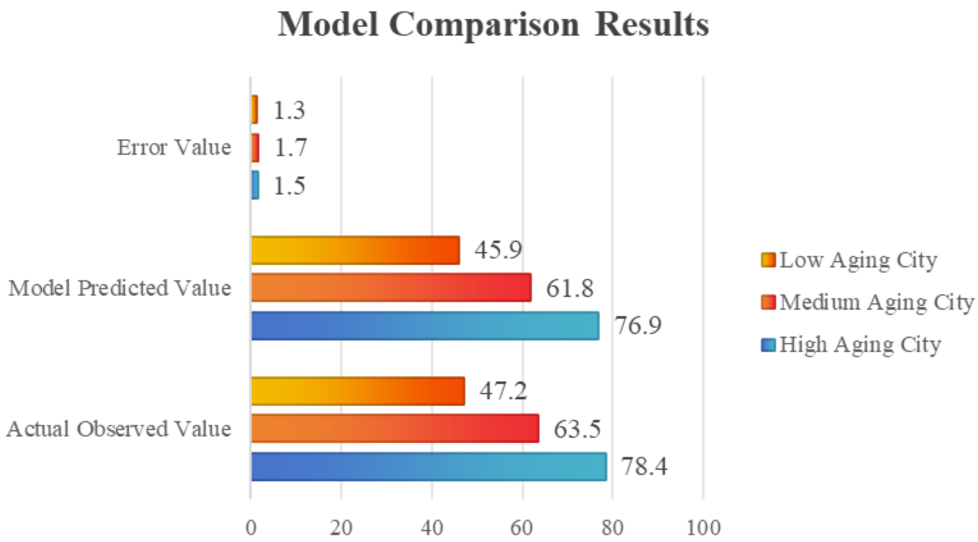

Figure 4. Model comparison results.

Pressure response model verification

The model was validated by comparing the predicted values to actual observed data. Regression analysis indicated a high goodness of fit with a coefficient of determination (R^2) of 0.87 and a RMSE of 6.32. These results confirmed the model's accuracy and stability in reflecting the dynamic influence of aging on ecological pressure. The verification of the model showed that it could effectively predict the environmental response under different aging pressures, and the model's performance improved with optimization (Figure 4).

Summary and key insights

The results demonstrated that aging had a significant, nonlinear effect on urban ecological pressures, especially in cities with high aging populations. The environmental stress associated with aging was more pronounced in these cities as they faced increased energy consumption, waste emissions, and reduced resource utilization efficiency. Additionally, the simulation results showed that comprehensive intervention measures including optimal resource allocation and environmental management strategies could mitigate the negative effects of aging on the ecological environment. The model's accuracy was confirmed through parameter optimization and validation, although some limitations remained in dealing with extreme scenarios and infra-regional heterogeneity. The model may not fully capture the variation in ecological pressure across different regions due to the simplified assumptions about some variables.

Policy recommendations and conclusion

Based on the study results, a comprehensive management strategy should be prioritized to address the interactive impact of aging and ecological pressure. In cities with high aging pressure, green technologies such as low-carbon energy and waste resource utilization should be developed to improve urban environmental capacity. Ecological governance policies needed to be accelerated in medium-aging cities to strengthen pollution control and optimize public resource allocation. In cities with low aging pressure, a forward-looking ecological protection mechanism should be established, focusing on long-term planning to prevent future ecological degradation risks. Additionally, the integration of intelligent ecological management models including machine learning algorithms and real-time monitoring could optimize resource allocation and track the restoration of ecosystems in real time, facilitating more efficient governance. This study provided valuable insights into the ecological impacts of aging populations and offered actionable strategies to mitigate these impacts, promoting the sustainable development of urban ecosystems in the context of demographic changes.

References

1. Mohagheghi V, Mousavi SM, Antucheviciene J, Mojtahedi M. 2019. Project portfolio selection problems: a review of models, uncertainty approaches, solution techniques, and case studies. Technol Econ Dev Econ. 25(6):1380-1412.
2. Harrir MM, Sari LT. 2024. Exploring the power of artificial intelligence in supply chain management: a literature review on the artificial intelligence applications and tools used in supply chains and their distribution according to the SCOR method. Eng Manag J. 1-22.
3. Aydin M, Karal H, Nabiyev V. 2023. Examination of adaptation components in serious games: a systematic review study. Educ Inf Technol. 28(6):6541-6562.
4. Wang M, Zhuang JA, Sun CH, Wang L, Zhang MH, Fan CL, *et al*. 2024. The application of rain gardens in urban environments: A bibliometric review. Land. 13(10):1702.
5. Mofrad F, Ignatieva M. 2024. From a grassland to a bush capital: A historic review of Canberra's green infrastructure development. Environ Hist. 30(3):419-447.
6. Fernández-Ballbé O, Martin-Moratinos M, Saiz J, Gallardo-Peralta L, de Roda ABL. 2023. The relationship between subjective aging and cognition in elderly people: A systematic review. Healthcare. 11(24):3115.
7. Paudel S, States SL. 2023. Urban green spaces and sustainability: Exploring the ecosystem services and disservices of grassy lawns versus floral meadows. Urban For Urban Greening. 84:127932.
8. Li Z, Zhang WG, Duan YT, Niu Y, Chen YZ, Liu XM, *et al*. 2023. Progress in biological age research. Front Public Health. 11:1074274.
9. Goldman EA, Sterner KN. 2023. Environment, epigenetics, and the pace of human aging. Annu Rev Anthropol. 52:279-294.
10. Pitt TM, Aucoin J, HubkaRao T, Goopy S, Cabaj J, Hagel B, *et al*. 2021. The relationship of urban form on children and adolescent health outcomes: a scoping review of Canadian evidence. Int J Environ Res Public Health. 18(8):4180.
11. Semeraro T, Scarano A, Buccolieri R, Santino A, Aarrevaara E. 2021. Planning of urban green spaces: an ecological perspective on human benefits. Land. 10(2):105.
12. Teater B, Chonody JM. 2020. How do older adults define successful aging? A scoping review. Int J Aging Hum Dev. 91(4):599-625.
13. Foo H, Mather KA, Thalamuthu A, Sachdev PS. 2019. The many ages of man: Diverse approaches to assessing aging-related biological and psychological measures and their relationship to chronological age. Curr Opin Psychiatry. 32(2):130-137.
14. Wisnesky UD, Kirkland SW, Rowe BH, Campbell S, Franc JM. 2022. A qualitative assessment of studies evaluating the classification accuracy of personnel using start in disaster triage: A scoping review. Front Public Health. 10:676704.
15. Ding XE, Zheng MR, Zheng XQ. 2021. The application of genetic algorithm in land use optimization research: a review. Land. 10(5):526.