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Causal Analysis and Adaptive Governance of Carbon Emission Networks under Multiscale Land Use Dynamics in Smart Cities

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Abstract. As the global city continues to develop, it becomes an important route for the development of the city. Science and detailed discharge management industry promotion city green color track type equipment with key image. Factors such as construction exclusion, basic space change, land use flow influence construction density, energy consumption and transportation activity, etc. However, there is currently a lot of research, analysis of the current situation, the stagnation of scarce land use, change of land use, exclusion and release, exploration of non-green and multi-route guidance mechanical systems, the provision of city management and the dependence on the current drought. This study provides an example of a high-density city city, Hong Kong, a PCCMCI for construction + a causal effect calculation method, a structured land use-exclusionary causal chain model, and a system. Recognizing different types of land use change, the impact of stagnation on land use, and the combination of different analysis methods and the selection of appropriate control points for pipe construction. Based on seasonal frequency analysis from 2000 to 2022, research joint analysis, article 37, causal path by Akira. Among them, the residential land has the most prominent effect, with a 1.5-season period, and the causal strength is 0.68; the commercial land has a 2-season period, and the causal strength is 0.72. The green land area will be reduced by 10% each time, and the current area will be released by 8.3%. The number centrality analysis progress is shown in Hong Kong East Business District, Nine Long Central Transportation Center and New Territories Southwest Industrial Corridor, the number centrality division is 0.847, 0.782 and 0.634. This study provides wisdom city background review, system support, and support for dynamic decision-making in Hong Kong. If you are interested in other high-density city cities, you can apply for additional power and support during the course of the exhibition.

Keywords: Smart Cities, Land Use, Carbon Emission Network, Causal Inference, Adaptive Governance

1. Introduction

With the acceleration of global urbanization, smart cities have become an important pathway to achieving sustainable development goals. As a key component of smart city construction, the

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scientific and refined management of carbon emissions directly affects the effectiveness of green urban transformation [1]. Land use, as a fundamental spatial variable of carbon emissions, influences carbon levels indirectly by affecting building density, energy consumption, and traffic activities, forming a complex causal system with dynamic feedback characteristics [2]. However, existing studies mostly remain at the level of static correlation, lacking in-depth analysis of the lagged, nonlinear, and multi-path transmission relationships between land use changes and carbon emissions, making it difficult to provide timely intervention strategies for urban governance [3]. As a typical high-density city, Hong Kong will have a mid-year population of about 7.52 million by 2024, with an overall population density of about 6,900 persons/km², resulting in a high degree of agglomeration of population and activities in a very small space. At the same time, its developable land is extremely limited. Of the total land area of about 1,111 km², only about 24.3% (about 270 km²) is built-up area, while the remaining 75.7% is non-built-up or undeveloped land, about 40% of which is designated as country parks and special areas, resulting in a structural contradiction of "High Population Density - Low Developability Ratio". About 40% of them are designated as country parks and special areas, resulting in a structural contradiction of "high population density - low developable ratio". This unique spatial-population constraint pattern makes energy-intensive activities such as residential, commercial and transportation activities superimposed and amplified in the limited space, resulting in a significant lag effect of carbon emissions in time, and a cross-scale propagation and strong feedback characteristics in space, which is the basis for the construction of the "land use-carbon emission" time-lag model using PCMCI+ in this paper. This also provides a solid practical background and theoretical motivation for this paper to use PCMCI+ to construct a time-lag causal network of "land use" and "carbon emission", and to identify the key governance nodes based on the structure of the network and propose adaptive regulation strategies.

Therefore, this study takes the high-density city of Hong Kong as an example, applies the PCMCI Plus lagged causal discovery algorithm to construct a land use–carbon emission causal network model, systematically identifies the lagged impact paths of different land use changes on carbon emissions, and further proposes key governance nodes and adaptive regulatory recommendations based on network structure analysis. The aim is to provide mechanism-based and data-driven support for carbon governance strategies in smart cities.

2. Literature review

2.1. Land use change and carbon emission interactions

Land use change is widely regarded as a key factor affecting urban carbon emissions. Its mechanism of action primarily involves altering urban spatial structure and functional layout, thereby adjusting energy efficiency, traffic intensity, and the carbon sink capacity of ecosystems [4]. Existing studies have extensively adopted remote sensing interpretation and regression analysis methods to reveal significant positive relationships between construction land expansion and green space compression on carbon emissions [5]. They have also indicated that industrial restructuring, urban sprawl, and traffic accessibility exert nonlinear moderating effects. However, such studies are largely based on correlation testing and fail to effectively distinguish the temporal order and lag effects between variables, resulting in difficulties in determining which changes occur first and which emissions follow. This weakens the temporal sensitivity and precision of policy intervention [6]. Especially in multi-scale urban systems, there exist interactive coupling effects across different spatial levels such as neighborhoods, streets, and administrative districts. Simple land use statistical models are insufficient to characterize the real evolution logic, creating a gap between cognitive understanding

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and regulatory implementation. In addition, there is a lack of systematic comparison across studies regarding the transmission paths and strengths of different land use types within carbon emission causal networks, preventing the establishment of governance priority sequences based on causal mechanisms [7]. Therefore, it is urgent to shift land use research from static spatial modeling toward dynamic causal identification frameworks to more accurately reflect the multi-stage driving processes of carbon emissions in evolving urban systems.

2.2. Carbon emission network modeling in smart cities

With the continuous advancement of smart city development, data-driven urban carbon emission modeling has become an important component of digital urban governance. Current modeling approaches mainly include estimation models based on remote sensing and statistical data, spatial distribution prediction models integrating multi-source datasets, and urban emission network models using graph theory [8]. Some recent studies have introduced graph neural networks and causal learning algorithms to identify structural association features within emission pathways. These methods contribute to improving the accuracy and spatial resolution of emission detection, yet remain insufficient in capturing the real mechanisms of interaction between land use change and the emission system [9]. On one hand, most models are based on static time snapshots and cannot reveal the temporal sequence features or lagged drivers behind emission changes. On the other hand, the structural dependencies among variables are often predefined or based on empirical rules, lacking the ability to automatically extract causal relationships from data. As a result, modeling outcomes are sensitive to data distribution assumptions and variable selections [10]. More importantly, existing emission network modeling generally overlooks the cross-scale interactive structure between land use and carbon emissions, namely how local land activities transmit through the network to influence macro-level emission changes. There is a lack of identification of carbon emission propagation and transmission nodes [11]. Therefore, emission network modeling for smart city governance urgently needs to incorporate lagged causal discovery algorithms with strong interpretability, enabling dynamic capture of land use-driven pathways and identification of key nodes to support the formulation of mechanism-based urban carbon governance strategies.

2.3. Causal discovery in urban governance

In recent years, causal inference methods have attracted increasing attention in urban system research, particularly for their strong capabilities in handling high-dimensional time series data, evaluating policy intervention effects, and analyzing system feedback mechanisms. Compared with traditional correlation analysis and regression modeling, causal inference clarifies the directionality and lag relationships between variables, thus providing more timely and actionable decision support for urban planning [12]. PCMCI Plus, as a causal discovery algorithm suitable for high-dimensional, nonlinear, and multi-lag systems, combines conditional independence testing with temporal structure modeling. It effectively extracts true lagged causal chains from multivariate sequences while eliminating spurious correlations and has been applied in complex systems such as climate science and environmental system analysis [13]. Applying this algorithm to land use and carbon emission modeling in urban contexts can overcome the limitations of traditional analyses in causal identification and reveal the multi-stage evolution logic of land change preceding carbon response. It is particularly suitable for governance scenarios in smart cities characterized by strong dynamic feedback and complex regulatory cycles [14]. Moreover, the structure of causal networks inherently supports visualization and interpretability, making it easier for policymakers to identify key drivers

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and formulate targeted interventions. Unlike indicator-based static planning, causal inference-based urban planning emphasizes process orientation and dynamic response, enabling a shift from ex-post evaluation to feedforward intervention. However, the current application of causal inference in urban planning remains limited. Most studies focus on technical implementation while lacking effective integration with governance tools, spatial policies, and administrative processes [15]. Therefore, future research should promote deep integration between causal analysis and multi-scale urban planning systems, achieving a closed-loop application from data to mechanism to decision-making.

3. Methodology

3.1. Data collection and preprocessing

Hong Kong is selected as a typical case of high-density smart city in the study, and a multi-scale spatio-temporal dataset is constructed from 2000 to 2022, with five years as a time node for stage-by-stage analyses. The data collection covers four major categories, namely remote sensing imagery, carbon emission estimation, urban activities and auxiliary control variables, to ensure data completeness and spatio-temporal consistency for causal modelling. As shown in table 1.

Table 1. Multi-source data types, contents, and sources

Data Type	Specific Content	Data Source	Temporal Resolution	Spatial Resolution
Remote Sensing Data	Multispectral satellite imagery, NDVI vegetation index	Landsat 5/7/8 (USGS), Sentinel-2 (ESA)	Quarterly	30m × 30m
Land Use Classification	Residential, commercial, industrial, green space, water, transportation	Processed via deep learning segmentation of satellite imagery	Quarterly	1km × 1km
Carbon Emission Data	Building energy use, traffic emissions, industrial emissions	Hong Kong EPD, EDGAR v6.0	Quarterly	1km × 1km
Urban Activity Data	Population density, building density, traffic volume	Hong Kong Census, Transport Department	Annual/Quarterly	1km × 1km
Meteorological Data	Temperature, humidity, wind speed, precipitation	Hong Kong Observatory	Daily average	Interpolated from station data
Policy Intervention Data	Major planning policies, infrastructure project timelines	Hong Kong Planning Department	Event-based	Regional level

In terms of data preprocessing, the bicubic interpolation method is first used to uniformly resample heterogeneous data to a 1km×1km grid to achieve high-precision spatial registration; secondly, the missing values are repaired by sliding window averaging and cubic spline interpolation to ensure the continuity of the time series [16]. Land use classification is based on remote sensing semantic segmentation based on the improved UNet deep learning model, with a classification accuracy of 92.3%. Carbon emission estimation adopts a bottom-up inventory method, integrating building energy consumption, traffic surveys, and industrial emission monitoring data for spatiotemporal interpolation. All variables are Z-value standardized to eliminate the interference of scale differences on causal analysis.

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3.2. Causal network construction with PCMCI+

PCMCI+ (PC algorithm with Momentary Conditional Independence Plus) serves as an advanced lagged causal discovery algorithm that can identify genuine causal relationships in high-dimensional nonlinear systems while eliminating spurious correlations [17]. This algorithm effectively handles complex lagged effects and nonlinear transmission mechanisms between land use changes and carbon emissions through the combination of conditional independence testing and temporal structure modeling.

The algorithm's core lies in causal relationship determination based on conditional independence. For testing the causal relationship between variables $X_i^{(t-\tau)}$ and $Y_j^{(t)}$, the algorithm first calculates the conditional independence statistic:

$$I\left(X_i^{(t-\tau)};Y_j^{(t)}|Z^{(t-1)}\right)=\sum_{x,y,z}p\,(x,y,z)\log\frac{p(x,y|z)}{p(x|z)p(y|z)} \tag{1}$$

Where $Z^{(t-1)}$ represents the conditional variable set at time t−1, and τ denotes the lag time step. When $I\left(X_i^{(t-\tau)};Y_j^{(t)}|Z^{(t-1)}\right)>\alpha$ (significance threshold), a lagged causal relationship from Xi to Yj is considered to exist.

To handle nonlinear relationships and mixed data types, the algorithm employs permutation-based non-parametric testing methods. For continuous variables, partial correlation coefficients are used as test statistics:

$$\rho_{X_i^{(t-\tau)},Y_j^{(t)}|Z^{(t-1)}}=\frac{\rho_{X_i^{(t-\tau)},Y_j^{(t)}}-\sum_k\rho_{X_i^{(t-\tau)},Z_k^{(t-1)}}\cdot\rho_{Z_k^{(t-1)},Y_j^{(t)}}}{\sqrt{\left(1-\sum_k\rho^2_{X_i^{(t-\tau)},Z_k^{(t-1)}}\right)\left(1-\sum_k\rho^2_{Z_k^{(t-1)},Y_j^{(t)}}\right)}} \tag{2}$$

The optimized version of the algorithm introduces Momentary Conditional Independence (MCI) testing, which can simultaneously consider lagged causal relationships and contemporaneous associations. MCI testing iteratively identifies the true causal parent node set through an iterative elimination algorithm, with the iterative update formula:

$$PC_j^{(t)}=\left\{X_i^{(t-\tau)}:I\left(X_i^{(t-\tau)};Y_j^{(t)}|PC_j^{(t)}\setminus\left\{X_i^{(t-\tau)}\right\}\right)>\alpha,\forall\tau\in[1,\tau_{max}]\right\} \tag{3}$$

This process eliminates indirect associations and spurious correlations through stepwise conditioning, ultimately constructing a directed acyclic graph reflecting the true causal structure. In this study, the maximum lag step $\tau_{max}=8$ (corresponding to 2 years) and significance level $\alpha=0.05$ were set to ensure accuracy and robustness of causal discovery.

3.3. Governance mapping based on network analysis

After causal network construction, graph-theoretic analysis methods are employed to identify key nodes and propagation pathways in the network, providing precise intervention strategies for smart city carbon emission governance. Network analysis combines topological structural features with causal strength weights, achieving effective transformation from mechanism discovery to governance practice.

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Network centrality analysis serves as the core method for identifying key governance nodes. Degree centrality is first calculated to quantify the direct influence range of each node in the causal network:

$$C_D(v_i) = \frac{\sum_{j \neq i} a_{ij}}{N-1} \tag{4}$$

Where a_{ij} represents the weighted adjacency matrix element from node i to node j, with weights representing causal strength, and N is the total number of network nodes. Nodes with high degree centrality indicate extensive direct influence in the causal network and are priority targets for governance.

Betweenness centrality further identifies key transmission nodes in the network, which serve as bridges in multiple causal pathways:

$$C_B(v_k) = \sum_{i \neq j \neq k} \frac{\sigma_{ij}(v_k)}{\sigma_{ij}} \tag{5}$$

Where σij represents the number of shortest paths from node i to node j, and $\sigma_{ij}(v_k)$ represents the number of shortest paths passing through node k. Intervention on nodes with high betweenness centrality can achieve cascading control effects across the entire network, making them crucial for maximizing governance efficiency.

To quantify the propagation strength of causal pathways and governance priorities, a path weight accumulation indicator is introduced. For causal pathways P_{ij} from land use change node Li to carbon emission node Cj, the propagation strength is calculated as:

$$W(P_{ij}) = \prod_{(u,v) \in P_{ij}} w_{uv} \cdot e^{-\lambda d_{ij}} \tag{6}$$

Where w_{uv} represents the causal strength weight between adjacent nodes on the path, dij is the path length, and λ is the distance decay parameter. This indicator comprehensively considers causal strength and propagation distance, accurately evaluating the potential effects of different land use intervention strategies.

Based on network analysis results, a multi-level adaptive governance framework is constructed. Through cluster analysis, the causal network is divided into different functional modules, identifying core driving modules, transmission mediating modules, and response accepting modules. Combined with Hong Kong's urban spatial structure characteristics, network analysis results are mapped to specific geographical regions and policy tools, forming a closed-loop governance system of "identification-warning-intervention-evaluation" that provides scientific basis and decision support for precise carbon emission governance in smart cities.

4. Experimental results

4.1. Identified causal pathways

The land use-carbon emission causal network constructed using the PCMCI+ algorithm revealed complex lagged causal relationship patterns in Hong Kong's urban system. Through analysis of quarterly data from 2000-2022, the study identified 37 significant causal pathways, with construction land expansion showing pronounced lagged effects on carbon emissions. Specifically, residential land expansion exhibited the strongest impact on carbon emissions after a lag of 1.5

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quarters, with a causal strength of 0.68 ($p<0.001$), while commercial land expansion reached its peak impact at a 2-quarter lag with a causal strength of 0.72 ($p<0.001$). This temporal delay primarily stems from construction cycles in newly developed areas, infrastructure completion, and the gradual stabilization of energy consumption patterns after resident occupancy.

Green space reduction demonstrated markedly different temporal patterns, characterized by immediate and short-term concentrated effects. Analysis results show that a 10% reduction in green space area led to an 8.3% increase in regional carbon emissions in the current period, with the impact further amplifying to 12.1% within a 1-quarter lag. This rapid response mechanism is primarily attributed to the immediate loss of carbon sink functions, intensification of urban heat island effects, and the resulting surge in air conditioning energy consumption. Industrial land exhibited more complex impact patterns with multi-stage transmission characteristics. Industrial land expansion first caused a 15.7% increase in transportation activity intensity within a 1-quarter lag, subsequently affecting commercial area carbon emissions through supply chain linkage effects within 2-3 quarters, ultimately forming cross-regional cascading amplification effects.

4.2. Central nodes and governance priorities

Causal network topology analysis reveals key governance nodes in Hong Kong's urban carbon emission system (Figure 1). Based on the network centrality index, this study identifies strategic priority intervention areas. The betweenness centrality of the Eastern Business District of Hong Kong Island is the highest (0.847), followed by the Kowloon Transportation Hub (0.782) and the Southwest Industrial Corridor of the New Territories (0.634). The three play a key "bridge" role in the carbon emission causal chain. For these nodes, carbon emission trading quota regulation, differentiated energy tax rates or green building standards can be introduced to maximize the governance leverage effect.

The out-degree centrality analysis shows that the core business district of Hong Kong Island dominates 92.3% of the network node influence with an index value of 0.923, indicating that it is a key driver of carbon emissions. It is recommended that the region curb the high-carbon expansion path by strengthening the carbon budget assessment mechanism in land development approval and promoting energy performance contracts (EPC).

The closeness centrality results indicate that the Central District (0.856) has an advantage in response speed in the entire network and is suitable as an emergency response and policy pilot area. It can be deployed with priority for real-time carbon monitoring systems and dynamic control tools (such as adjustable peak and valley electricity prices). Although the emission intensity of the New Territories fringe area is relatively low (0.34 tons of CO_2/km^2), its radiation impact coefficient is as high as 2.67, indicating that the indirect diffusion effect between the "edge-core" is significant. The system collaborative governance should be strengthened by regulating cross-regional commuting flows and optimizing the industrial supply chain structure.

Modularity analysis identified four functional clusters: Hong Kong Island Financial and Commercial District (0.78), Kowloon Manufacturing District (0.65), New Territories Residential Development District (0.52) and Cross-border Logistics District (0.41). Differentiated governance tools should be matched for different clusters, such as promoting green supply chain assessment in the manufacturing cluster, introducing carbon credit incentive mechanism in the residential development district, and implementing clean transportation policies in the logistics cluster, so as to achieve both precise and systematic carbon emission management.

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Figure 1. Hong Kong carbon emission network: central nodes and governance priorities

5. Conclusion

This study successfully revealed the causal relationships and lagged impact mechanisms of land use dynamics on carbon emissions in smart city contexts through the PCMCI+ lagged causal discovery algorithm. The research achieved a significant methodological transition from static correlation analysis to dynamic causal identification, effectively addressing technical challenges in time series and lag effect identification in traditional studies. By constructing multiscale land use-carbon emission causal networks, this study identified 37 significant causal pathways, quantified the lagged impact intensities and transmission mechanisms of different land use types, providing scientific foundations for precision carbon governance.

Network centrality analysis further identified key governance nodes and functional clusters, offering spatially-targeted guidance for adaptive governance strategy formulation. The successful practice of Hong Kong's case demonstrates the effectiveness and operability of causal network analysis in smart city carbon management, providing a replicable governance framework for other high-density urban centers pursuing climate resilience and sustainability. The research outcomes contribute to promoting a fundamental shift in urban planning from ex-post evaluation to feedforward intervention, achieving data-driven precision governance.

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