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Can Green Infrastructure Curb Urban Sprawl? Evidence from China's Sponge City Program and Spatial Implications for Emerging Asia

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Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Author contribution

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Can Green Infrastructure Curb Urban Sprawl? Evidence from China's Sponge City Program and Spatial Implications for Emerging Asia

Abstract: Motivated by the global challenges of unsustainable urban expansion and climate vulnerability, China implemented the Sponge City Program (SCP) as a large-scale nature-based intervention. Moving beyond its conventional framing as a purely hydraulic tool, this study re-evaluates the SCP as a catalyst for spatial governance. Utilizing a Double Machine Learning (DML) approach on spatial data from 279 Chinese cities (2011–2023), we examine the policy's capacity to curb inefficient urban sprawl (US). The results reveal that the SCP significantly restrains sprawl through enhanced energy efficiency, expanded green infrastructure, and increased urban polycentricity, particularly in central and non-resource-based cities. Ultimately, this study provides a globally transferable "double dividend" paradigm for emerging economies, demonstrating how green infrastructure investments can serve as proactive spatial governance instruments to steer sustainable urban morphologies.

Keywords: Sponge City; Urban Sprawl; Double Machine Learning; Urban Morphology; Spatial Governance; Green Infrastructure

1 Introduction

The rapid pace of urbanization, accompanied by inefficient urban sprawl (US), stands as a critical barrier to sustainable urban development (Chettry, 2022). Characterized by low-density, fragmented, and outward expansion, US not only accelerates the degradation of ecological spaces but also generates profound structural pressures on high-quality urban growth. This challenge is particularly pronounced across the Asia-Pacific region, where cities in emerging economies increasingly face the dual threats of low-density expansion and climate-induced hydrological crises (Dodman et al., 2022). In China, where rapid economic growth has intensified the tension between urban land expansion and ecological carrying capacity, this challenge is especially acute. If left unaddressed, continued sprawl will aggravate water shortages, resource inefficiency, and ecological degradation, revealing the unsustainability of traditional extensive growth models (Kang et al., 2021).

To contain unchecked expansion, policymakers globally have implemented various spatial governance strategies. Traditional land-use controls, such as Urban Growth Boundaries (UGBs), often face limitations due to their rigid regulatory nature, high enforcement costs, and potential market distortions (Schuster Olbrich et al., 2022). Consequently, urban planning has increasingly embraced "Smart Growth" and nature-based solutions, emphasizing compact land use and green infrastructure (Park, 2023). However, in advanced Western economies, green infrastructure policies—such as Low Impact Development (LID) in the US or Sustainable Urban Drainage Systems (SUDS) in the EU—are typically implemented as decentralized, site-specific engineering codes driven by market mechanisms or localized environmental regulations (Qiao et al., 2018). While effective in mature, slow-growing cities, these fragmented approaches often lack the macro-spatial regulatory power required to guide the explosive and often disordered urban expansion typical of the Global South. Within this context, China introduced the Sponge City Program (SCP)—a massive nationwide initiative initially designed to mitigate urban flooding and foster a sustainable balance between urbanization and environmental resources (Zeng et al., 2023). Originating from Western stormwater management practices, the sponge city concept has been thoughtfully adapted from a localized hydraulic tool into a state-led, macro-spatial governance strategy to address the distinct developmental challenges of transitional economies (Fletcher et al., 2015). While a growing body of literature has extensively documented the ecological and climate-adaptive benefits of the SCP, it remains predominantly conceptualized as a purely hydraulic engineering intervention.

This conventional framing overlooks the profound spatial implications of large-scale green infrastructure investments under a strong-government framework. Existing studies either focus on the rigid constraints of traditional planning tools or isolate the SCP within the domain of water management. Specifically, it remains an unresolved empirical puzzle whether such top-down green policies proactively steer urban morphological transformation. Theoretically, the SCP facilitates a critical transition in built-up areas from a pattern of “incremental expansion” to one focused on “optimizing the existing stock” (Fu et al., 2023). Through comprehensive upgrades to drainage systems, road networks, and landscape design, it establishes ecological thresholds that can curb inefficient land use and the compression of ecological spaces (Pille & Säume, 2021; Zhang et al., 2022).

In practice, however, the policy may produce unintended consequences. A unique institutional driver of urban expansion in China and many other Asian emerging economies is the structural reliance of local governments on land-based finance, where land leasing serves as a primary source of fiscal revenue (UN-Habitat, 2016). Local governments, driven by land-based finance, might leverage sponge city projects to catalyze new district development, potentially turning green infrastructure into a catalyst for further sprawl. Assessing the SCP’s capacity to serve as an endogenous "physical constraint" against such entrenched economic incentives offers profound insights into the interplay between ecological policy and institutional economics. Moreover, funding gaps, inconsistent technical standards, and inadequate interdepartmental coordination in some projects further constrain their effectiveness in containing urban expansion. Given these competing forces, the effect of the SCP on US is far from self-evident. We hypothesize that, despite localized risks of expansionary abuse, the rigorous ecological thresholds and infrastructure investments mandated by the SCP predominantly act as a containment mechanism, reshaping urban form toward compactness.

To bridge this gap, this study re-evaluates the SCP not merely as a flood-mitigation tool, but as a strategic instrument for spatial governance and urban restructuring. Utilizing fused nighttime light datasets and an advanced Double Machine Learning (DML) framework across 279 Chinese cities (2011–2023), we provide novel causal evidence on how the policy restrains US. The key contributions are threefold. First, methodologically, we overcome the "curse of dimensionality" and confounding biases inherent in traditional econometric approaches (such as DID) by applying the DML framework. This robust identification allows us to empirically demonstrate that green infrastructure investments can endogenously curb sprawl, offering a state-led spatial governance paradigm that contrasts with the decentralized, site-specific green policies typical of Western contexts. Second, we unpack this containment effect by identifying three distinct socio-spatial pathways: reducing the energy intensity of the built environment, enhancing the spatial provision of multi-functional green infrastructure, and fostering polycentric urban morphologies. These mechanisms speak directly to the 'double dividend' of environmental sustainability and compact urban growth. Third, through heterogeneity analysis, we offer a context-sensitive understanding of how varying environmental baselines, resource endowments, and city hierarchies dictate the efficacy of this spatial governance tool, arguing against universal policy blueprints.

2 Theoretical framework and research hypothesis

2.1 Urban Sprawl and Conventional Spatial Governance

US has long been characterized by leapfrog development, commercial strip expansion, and low-density single-use subdivisions that produce fragmented, low-accessibility suburban landscapes (Ewing, 1997). In the Chinese context, it is commonly defined as a condition of imbalance wherein the growth rate of built-up land substantially outpaces population urbanization, resulting in declining urban density and inefficient land use (Li & Li, 2019). The drivers of this phenomenon are multi-dimensional. While Western contexts often attribute sprawl primarily to market failures and consumer preferences (Osman et al., 2016), urban expansion in China has evolved under the dual influence of market dynamics and government-led institutional incentives, including fiscal pressures and lagging land management reforms (Wang et al., 2021; Zhang & Han, 2024).

The consequences of this fragmented expansion are well-documented, generating significant socio-ecological challenges ranging from the consumption of arable land to heightened public health risks and increased traffic congestion (Lopez-Aparicio et al., 2025; Genovese et al., 2023). To curb such unchecked expansion, policymakers have traditionally relied on rigid land-use instruments, such as Urban Growth Boundaries (UGBs). However, as these tools often face enforcement challenges and generate market distortions, the subsequent "Smart Growth" movement has increasingly emphasized compact urban forms. In this context, the integration of high-density infill development coupled with ecological infrastructure has gained recognition as a priority strategy to balance land demands with ecological limits (Wang et al., 2019c; Wen et al., 2024).

2.2 The Sponge City Program: Policy Transition and Morphological Tensions

Originating from Western stormwater management practices such as Low Impact Development (LID), the concept of the "sponge city" marks a pivotal advancement in China's urban planning paradigm (Fletcher et al., 2015; Li et al., 2017). The SCP facilitates a critical transition in built-up areas from a pattern of "incremental expansion" to one focused on "optimizing the existing stock" (Fu et al., 2023). Through comprehensive upgrades to drainage systems, road networks, and landscape design, the policy theoretically establishes ecological thresholds that curb inefficient land use and the compression of ecological spaces (Pille & Säume, 2021; Zhang et al., 2022).

While the ecological and water-management benefits of the SCP have received substantial attention (Wang et al., 2023; Bah et al., 2023), translating this hydrological initiative into spatial reality presents complex institutional trade-offs. Within the ongoing reliance on land-based finance in many Chinese cities, conflicting policy goals may cause sponge city principles to be compromised by short-term economic priorities. Some local governments may couple sponge city projects with aggressive new district development, potentially turning green infrastructure into a catalyst for further suburban sprawl rather than a containment tool.

Consequently, the potential role of this state-led initiative as an endogenous driver of urban morphological restructuring remains an empirical puzzle. Much of the current literature treats environmental policies merely as exogenous ecological constraints or focuses exclusively on their direct engineering outcomes. Although conceptual studies suggest that green infrastructure can optimize spatial layouts, empirical evidence leveraging robust quasi-experimental methodologies to isolate the true treatment effect of the SCP on macro-level sprawl remains relatively scarce. Specifically, in transitional economies where rapid urbanization challenges spatial efficiency, there is a pressing need to unpack how large-scale green investments reshape urban patterns through structural channels. By reframing the SCP within the domain of urban analytics, this study aims to provide credible causal evidence to address these remaining literature gaps.

2.3 Research Hypotheses

2.3.1T Direct Effect: Sponge City as a Spatial Constraint

SCP introduces innovative governance tools and actionable pathways to mitigate US (Figure 1). guided by compact city theory, the SCP seeks to enhance the environmental carrying capacity and livability of existing built-up areas. It prioritizes the containment of low-impact development facilities—such as green roofs, sunken green spaces, rain gardens, and ecological wetlands—within established urban zones, or the retrofitting of already developed areas. This focus encourages the enhancement and regeneration of the existing urban fabric, thereby reducing the pressure for outward, dispersed expansion (Yuan et al., 2023). On the other hand, traditional extensive urban expansion typically leads to problems such as land waste, imbalanced spatial structures, and ecological degradation (Xie et al., 2018). These issues create demand for large-scale grey infrastructure—including roads and drainage networks—to support the dispersed development pattern. Such infrastructure entails high construction and maintenance costs while delivering relatively low utilization efficiency. Grounded in infrastructure constraints theory, sponge cities enhance the population and economic carrying capacity of built-up areas by strengthening their hydrological resilience, ecological adaptability, and overall infrastructure efficiency. Meanwhile, the policy sets ecological thresholds for new urban developments, requiring sponge infrastructure systems to be planned and built concurrently. This raises both the ecological costs and regulatory requirements for new district development, thereby reducing the incentive for local governments and developers to engage in unchecked expansion. Together, these mechanisms—guided by ecological priorities and green development principles—form a systematic spatial production model that helps curb US. Based on the above, the research hypothesis is proposed.

H1： The implementation of the SCP significantly curbs US by imposing stringent ecological constraints on low-density peripheral expansion.

2.3.2 Indirect Mechanisms: Efficiency, Public Goods, and Structure

The interplay between urban development and energy transition lies at the heart of sustainable urban progress. As cities grow and expand, rising energy demands drive significant increases in energy consumption and carbon emissions. Therefore, lowering energy use, boosting energy utilization efficiency, and enhancing community livability have become central to achieving balanced and sustainable urban development (Khiali-Miab et al., 2024). SCP utilizes natural processes for water retention, infiltration, and purification, substituting conventional grey infrastructure with sponge-based facilities. This shift reduces the carbon emissions associated with traditional, energy-intensive infrastructure (Nguyen et al., 2020), thereby lowering overall energy consumption and enhancing urban energy utilization efficiency. For instance, sponge city facilities such as green roofs and vertical greenery provide substantial thermal insulation and cooling benefits, which decrease the energy required for building cooling. Permeable pavements help mitigate the urban heat island effect and improve local microclimates, reducing cooling demand at the neighborhood scale. Additionally, optimized water recycling systems minimize the energy costs of long-distance water transfer. Improving energy utilization efficiency not only drives progress in energy conservation and emission reduction but also serves as a strategy to curb US (Sarkodie et al., 2020). By lowering the demand for resource-intensive expansion onto new construction land, it enhances the environmental sustainability and ecological service value of existing built-up areas, thereby helping to suppress low-density spatial expansion. Based on the above, the research hypothesis is proposed.

H2：The SCP inhibits US by enhancing energy utilization efficiency of the built environment and improving urban metabolic efficiency.

Residential sprawl represents a distinct form of US, driven by the expansion of residential developments such as new towns and urban districts. It is characterized by population migration into low-density urban peripheries, with its underlying driver being residents' pursuit of improved living conditions (Yan et al., 2022). From an environmental standpoint, deteriorating urban pollution intensifies health concerns among residents, encouraging movement from heavily polluted city centers to suburban areas. This demographic shift stimulates investment from property developers and increases land-based financing, further accelerating land expansion (Juan et al., 2022). The growth of built-up areas, accompanied by the loss of green spaces, agricultural land, and bare ground, not only raises the risk of natural disasters but also undermines ecosystem carbon storage capacity and ecological resilience (Imanpour et al., 2025). Green infrastructure serves as the foundational component of sponge cities. Pilot programs enhance both the ecological service functions and livability of urban areas by strategically guiding and investing in high-quality, interconnected green infrastructure networks, thereby increasing their attractiveness for residents and economic activities. At the same time, large-scale ecological corridors or green wedges establish ecological buffer zones that promote infill development within existing urban boundaries and help curb outward expansion toward urban fringes (Vargas-Hernández & Zdunek-Wielgołaska, 2021). Based on the above, the research hypothesis is proposed.

H3： The SCP curbs US by enhancing the spatial provision of green infrastructure, thereby improving core livability and anchoring infill development.

From a spatial perspective, US exhibits two dimensions: horizontal expansion and vertical expansion. The former refers to the outward extension of built-up areas (Oueslati et al., 2015), while the latter denotes the transformation of cities from monocentric to polycentric structures, giving rise to multifunctional agglomeration zones that reflect an optimized spatial configuration (Xiao et al., 2024). Pilot policies have facilitated concentrated investment in sponge infrastructure within designated zones, fostering the emergence of new development hubs. However, SCP does not entail uniform or blanket implementation; rather, it relies on strategic planning that integrates urban renewal, new district development, and key ecological nodes. This approach promotes the formation of new growth centers equipped with integrated ecological infrastructure within the existing single-center framework. The degree of urban polycentricity plays a critical role in constraining sprawl and promoting compact urban growth. Higher levels of polycentricity encourage development patterns characterized by “compact” and “infill” growth, whereas lower levels increase the likelihood of “edge-driven expansion” and “spontaneous sprawl” (He & Zhou, 2024). The evolution of urban spatial structure toward a multi-centered model enables functional differentiation within the city, reducing overreliance on a single central core and alleviating associated pressures such as long-distance commuting. As a result, urban development is steered toward intensive clustering around multiple ecological nodes, further preventing widespread low-density sprawl across the metropolitan area. Based on the above, the research hypothesis is proposed.

H4：The SCP curbs US by fostering a polycentric urban morphology and steering spatial growth toward compact secondary nodes.

Figure 1: Mechanism of SCP in Curbing US

3 Research Design

3.1 Model specifications

To address the "curse of dimensionality" and multicollinearity inherent in high-dimensional causal inference, we adopt the Double Machine Learning (DML) framework, which effectively compensates for the limitations of conventional econometric approaches (Chernozhukov et al., 2018; Díaz, 2020; Bach et al., 2021). The partially linear DML model is specified as follows:

$$Y_{it} = \theta_0 Event_{it} + g(X_{it}) + U_{it}, E(U_{it} \mid Event_{it}, X_{it}) = 0 \qquad (1)$$

Here, θ_0 denotes the treatment coefficient central to this study, reflecting the policy effect of “sponge city” pilot schemes on US; i represents the city, t denotes the year; Y_{it} is the dependent variable, signifying urban sprawl ; $Event_{it}$ is the treatment variable, i.e., the SCP, taking a value of 1 if city i becomes a pilot city in year t , and 0 otherwise; X_{it} denotes the set of high-dimensional control variables; function $g(X_{it})$ represents the nonlinear influence exerted by the high-dimensional vector on the dependent variable, requiring the use of machine learning algorithms to obtain the estimator $\hat{g}(X_{it})$; U_{it} is the error term, with an expected value of zero. To achieve unbiasedness and $\sqrt{n}$ -consistency, an auxiliary regression model is constructed to partial out confounding effects:

$$Event_{it} = m(X_{it}) + V_{it}, E(V_{it} \mid X_{it}) = 0 \qquad (2)$$

Here, $m(X_{it})$ denotes the regression function of the treatment variable on the high-dimensional control variables, requiring the use of machine learning algorithms to obtain the estimator $\hat{m}(X_{it})$; V_{it} represents the error term, with an expected value of zero.

The treatment coefficient estimator $\hat{\theta}_0$ obtained from the main equation (1) is biased, as estimator $\hat{\theta}_0$ fails to converge to θ_0 . Bias correction is required through an orthogonal method. Specifically, the error term V_{it} 's estimator $\hat{V}_{it} = Event_{it} - \hat{m}(X_{it})$ is derived from auxiliary equation (2), which in turn yields the unbiased estimator $\hat{\theta}_0 = (\frac{1}{n}\sum_{i \in I, t \in T} \hat{V}_{it} Event_{it})^{-1} \frac{1}{n}\sum_{i \in I, t \in T} \hat{V}_{it}(Y_{it} - \hat{g}(X_{it}))$ for θ_0.

3.2 Variable Selection

3.2.1 Dependent variable: US

Regarding the quantification of US, three main approaches are commonly employed: single-indicator metrics, comprehensive evaluation systems, and nighttime light data. For example, sprawl has been measured using a composite index that multiplies low-density area by low-density population, or by fitting an inverse-S-shaped urban land density function to model the decay of density from the city center outward, with sprawl then quantified by the ratio of suburban to core radial expansion rates (Jiao, 2015). Drawing on existing studies (Wang et al., 2019b; Ma et al., 2015), this paper measures US using nighttime light data. To minimize error, areas with corrected DMSP-OLS nighttime light brightness values of 6 or higher are delineated as urban zones. The US index is calculated using the following formula:

$$\text{sprawl} = L\% \,/\, H\%$$

Where $L\%$ denotes the proportion of urban area with light intensity below the national average relative to the total urban area, and $H\%$ represents the proportion of grid cells with light intensity above the national average. When sprawl > 1, US is present; when sprawl ≤ 1, no sprawl is observed. It should be noted, however, that the DMSP-OLS data is current to 2013. Based on this, and drawing upon relevant research (Huang et al., 2022; Wang et al., 2019a), this paper fused and calibrated DMSP-OLS data (2011–2013) with NPP-VIIRS data (2012–2023). This yielded a night-time light dataset for the period 2011–2023 at the DMSP-OLS scale, thereby characterizing US.

From 2015 to 2023, the US index in China demonstrated a pronounced spatial differentiation pattern characterized by lower values in the southeast and higher values in the northwest. In general, developed regions along the eastern coast—particularly core cities within major urban agglomerations such as the Pearl River Delta and Yangtze River Delta (e.g., Shenzhen, Shanghai, and Hangzhou)—exhibited relatively low sprawl indices (below 0.9), reflecting high levels of land use intensification and compact urban forms. In contrast, elevated sprawl indices (above 2.0) were observed in the northwest, northeast, and certain remote southwestern areas (such as Naqu, the Greater Khingan Range, and Jiuquan), indicative of extensive land coverage, low population density, and spatial expansion that outpaced demographic growth. This spatial distribution aligns closely with the "Hu Huanyong Line," a well-known demarcation corresponding to China's fundamental gradient in population density. See Figure 2.

Figure 2: Spatial Distribution of US Index in China (2015-2023)

3.2.2 Treatment Variable: SCP

The Ministry of Finance, the Ministry of Housing and Urban-Rural Development, and the Ministry of Water Resources initiated two batches of Sponge City pilot projects—30 cities in total—in 2015 and 2016. Based on the list of pilot cities, a policy dummy variable was constructed to indicate whether a city was included in the pilot program, and this variable serves as the treatment indicator in the analysis.

3.2.3 Control variables

To further control for variables that may influence US and ensure accurate estimation of policy effects, the following control variables are included: population size, measured by registered population; financial development, captured by the ratio of total deposits and loans of financial institutions to GDP; openness to the outside world, represented by the proportion of actual foreign capital utilization relative to regional GDP; urbanization level, defined as the share of non-agricultural population in the registered population; government intervention, indicated by the ratio of local government general budget expenditure to regional GDP; human capital, proxied by the enrollment in regular higher education institutions relative to the year-end total population; and fiscal decentralization, calculated as the ratio of local government general fiscal revenue to general fiscal expenditure. In addition, quadratic terms of these control variables are incorporated to account for potential nonlinearities and improve model fit. To address unobserved heterogeneity across cities and over time, city and year fixed effects are introduced using dummy variables for each city and each year.

3.2.4 Mechanism variables

This study aims to elucidate the mechanisms through which the SCP affects US via three pathways: energy utilization efficiency, green infrastructure, and the degree of urban polycentricity. To measure energy utilization efficiency, the SBM Malmquist-Luenberger index method is employed, with labor, capital, and energy as input variables, regional gross domestic product as the desired output, and emissions of industrial sulfur dioxide, industrial soot and dust, and industrial wastewater as undesirable outputs (Li & Chen, 2021; Meng & Qu, 2022). Green infrastructure is represented by the area of park green spaces. The degree of polycentricity is assessed through a two-step approach: first, a "centrality" indicator is constructed by integrating population distribution, land area, and spatial distances between urban centers; second, the degree of polycentricity is quantified by measuring the centrality equilibrium across these centers (Wang et al., 2023; Li & Liu, 2018). Specifically:

For each center j within the municipal area, its importance is defined as: $IMP_j = POP_j \times AREA_j \times DIS_j$, where POP_j denotes the center's population, $AREA_j$ denotes the center's area, and DIS_j denotes the spatial distance from the sub-center's centroid to the main center's centroid. The importance of the primary center is defined as: $IMP_{main} = POP_{main} \times AREA_{\max} \times DIS_{\max}$, where $AREA_{\max}$ represents the area of the largest center among all centers, and $DIS_{\max}$ denotes the distance between the primary center and the farthest secondary center. On this basis, the standard deviation $\sigma_{C,\text{obs}}$ of all central importance values is calculated and compared with the theoretical maximum standard deviation $\sigma_{C,\max}$ (i.e., the dual-centre extreme case) to derive the multi-centre degree indicator $\text{multicenter} = \left(1 - \frac{\sigma_{C,\text{obs}}}{\sigma_{C,\max}}\right) \times S$, which ranges from [0, 1]. Here, S represents the scale adjustment coefficient, defined as the ratio of the average distance from a city's sub-center to its main center to the maximum distance among all cities. This coefficient controls for the impact of urban scale differences on the indicator.

3.3 Data Sources and Descriptive Statistics

The study constructs a city panel dataset comprising 279 Chinese cities from 2011 to 2023 as the subjects of investigation. With the exception of US, which is measured using light-up data, all other data sources include the China Urban Statistical Yearbook, the China Urban Construction Statistical Yearbook, the LandScan Global Population Database, and the EPS Database. Additionally, in consideration of both data availability and scientific validity for the variables used, missing values were imputed through linear interpolation. Furthermore, natural logarithms were applied to certain variables to standardize their measurement scales. Descriptive statistics for these relevant variables are presented in Table 1.

Table 1 Descriptive Statistics

	Variable Name	Observations	Mean	Standard Deviation	Minimum Value	Maximum Value
Dependent variable	US	3627	2.653	2.054	0	21.967
Treatment Variable	SCP	3627	0.063	0.243	0	1
Control variables	Population size	3627	5.896	0.704	2.970	8.136
	Financial development	3627	2.650	1.260	0.588	21.301
	Openness to the outside world	3627	0.002	0.003	0	0.029
	Urbanization level	3627	0.402	0.215	0.075	1
	Government intervention	3627	0.202	0.101	0.044	0.916
	Human capital	3627	0.021	0.026	0.001	0.185
	Fiscal decentralization	3627	0.450	0.218	0.056	1.541
Mechanism variables	Energy utilization efficiency	3627	0.350	0.146	0.103	1.193
	Green infrastructure	3627	2.053	3.715	0.021	37.238
	Degree of urban	3627	0.357	0.189	0	0.901

	polycentricity

4 Empirical analysis

4.1 Baseline regression

Based on the theoretical analysis and research design outlined above, this paper employs a dual machine learning model to estimate the impact of sponge city pilot policies on US. Following the methodology established by Shen et al. (2024), a sample splitting ratio of 1:4 is utilized, with both main and auxiliary regressions being solved using the random forest algorithm. The regression results are presented in Table 2. The findings in Column (1) indicate that, after controlling for time fixed effects, city fixed effects, and first-order terms of control variables within the sample interval, the pilot policy has a statistically significant negative effect on US at the 1% level. This result confirms that SCP can effectively mitigate US, thereby validating hypothesis H1. Building upon Model (1), Column (2) further incorporates quadratic terms of the control variables to enhance precision. The regression coefficients remain significantly negative, providing additional support for the reliability of these findings.

Table 2: Baseline Regression Results

Variables	(1)	(2)
	US	US
SCP	-0.313***	-0.319***
	(0.106)	(0.107)
Control variable: first-order term	YES	YES
Control variable: second-order term	NO	YES
Time fixed effect	YES	YES
City fixed effect	YES	YES
Sample size	3627	3627

Note: *p<0.1, **p<0.05, ***p<0.01; values in parentheses denote robust standard errors; the same applies to the table below.

4.2 Robustness test

4.2.1 Outlier Removal

To eliminate the potential influence of extreme values, we applied 1% and 5% trimming to all continuous variables. As shown in Columns (1) and (2) of Table 3, the estimated coefficients of the SCP remain significantly negative at the 1% level, confirming that our baseline findings are not driven by outliers.

4.2.2 Exclude the impact of relevant policies

To isolate the SCP's treatment effect, we accounted for two major overlapping environmental initiatives: the Low-Carbon City pilot (2010) and the Key Air Pollution Control Zone policy (2013). Introducing dummy variables for these policies (Columns 3–5, Table 3) does not alter the significance or direction of the SCP's inhibitory effect on urban sprawl.

4.2.3 Reset DML Model

The potential influence of DML model specifications on baseline estimates was further addressed through the following robustness checks. First, the sample-splitting ratio of the DML model was altered from the baseline 1:4 to 1:5 and 1:7. As reported in Table 3, the estimated effect of the SCP on US remains statistically significant under these alternative ratios, with the coefficient retaining its negative sign and significance at the 1% level, confirming the robustness of the main result. Second, to mitigate potential bias arising from the choice of machine learning algorithm, the random forest estimator was replaced with gradient boosting. Results in Table 3 indicate that the SCP effect continues to be statistically significant, further supporting the reliability of the findings.

4.2.4 Placebo test

To rule out unobserved time-varying confounders and implicitly verify the parallel trends assumption, we conducted an in-time placebo test. We restricted the sample to the pre-treatment period (2011–2014) and artificially assigned a "fake" policy dummy to the treated cities for 2013 and 2014. As shown in Column (9) of Table 3, the coefficient for the "fake" SCP is statistically insignificant. This confirms that the observed containment of urban sprawl is genuinely driven by the actual SCP rollout rather than pre-existing divergent trends.

Table 3 Robustness Tests

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	1% trimmed tailing	5% trimmed tailing	low-carbon city	key air pollution control zone	dual policy	1:5	1:7	gradient boosting	PlaceboTest (Pre-2015)
SCP	-0.292***	-0.274***	-0.334***	-0.317***	-0.313***	-0.356***	-0.376***	-0.350***	
	(0.099)	(0.091)	(0.110)	(0.110)	(0.104)	(0.104)	(0.108)	(0.132)	
Fake SCP									-0.015
									(0.082)
Control variable: first-order term	YES	YES	YES	YES	YES	YES	YES	YES	YES
Control variable: second-order term	YES	YES	YES	YES	YES	YES	YES	YES	YES
Time fixed effect	YES	YES	YES	YES	YES	YES	YES	YES	YES
City fixed effect	YES	YES	YES	YES	YES	YES	YES	YES	YES
Sample size	3627	3627	3627	3627	3627	3627	3627	3627	1116

4.3 Endogeneity test

To address potential endogeneity concerns, we adopt an instrumental variable (IV) approach within the DML framework. Following Chernozhukov et al. (2018), the partially linear instrumental variable model is constructed as follows:

$$Y_{it} = \theta_0 Event_{it} + g(X_{it}) + U_{it}$$

$$Instrument_{it} = m(X_{it}) + V_{it}$$

In the equation, $Instrument_{it}$ is the instrumental variable for $Event_{it}$. First, following Wang et al. (2023), we employ the interaction between urban terrain slope and a post-2015 dummy as an instrument for SCP participation. For relevance, gentler plains facilitate green infrastructure implementation, thereby increasing a city's likelihood of SCP selection. For the exclusion restriction, terrain slope is a time-invariant geographical feature fully absorbed by city fixed effects; its interaction with the post-2015 dummy strictly isolates exogenous spatial-temporal variation from the national policy rollout. Second, drawing on local government competition theory, we construct a leave-one-out provincial adoption rate (the proportion of other intra-provincial cities implementing the SCP) as an alternative peer-group instrument. Regarding relevance, China's decentralized governance induces strong peer effects, where higher adoption among neighboring cities intensifies pressure for a focal city to participate. Regarding exogeneity, the policy decisions of *other* cities do not directly dictate the focal city's US.

As shown in Table 4, after controlling for endogeneity, the pilot policy maintains a significantly negative effect on US, confirming the robustness of the baseline findings.

Table 4: Endogeneity Test

Variables	Terrain slope	Peer-group IV
SCP	-36.955***	-19.138***
	（8.962）	（4.870）
Control variable: first-order term	YES	YES
Control variable: second-order term	YES	YES
Time fixed effect	YES	YES
City fixed effect	YES	YES
Sample size	3627	3627

4.4 Mechanism analysis

Having confirmed that the SCP significantly curbs US, we now explore the underlying mechanisms. Rooted in spatial economics and smart growth theories, we identify three mediating pathways: the enhancement of energy-use efficiency, the expansion of green infrastructure provision, and the promotion of urban polycentricity. Following the analytical approach of Chen et al. (2020), we estimate the SCP's direct impact on these mediators to quantitatively corroborate the theoretical linkages between policy intervention and spatial containment. The results are presented in Table 5.

4.4.1 Enhancement of energy utilization efficiency

The regression results in Table 5 show the SCP significantly improves energy utilization efficiency at the 1% level (by 0.081 units). From an urban metabolism perspective, overcoming the structural inertia typically associated with energy transitions represents a substantial optimization, confirming Hypothesis H2. Specifically, sponge facilities like permeable pavements and green roofs regulate microclimates, lowering surface temperatures and reducing buildings' operational energy consumption. Aligned with ecological modernization, this improvement reflects a structural shift: decreasing overall urban energy intensity and lessening the need to expand infrastructure footprints (e.g., wastewater treatment plants). Furthermore, the policy internalizes the hidden costs of low-density expansion, incentivizing developers toward infill redevelopment. By establishing ecological control lines and integrating sponge standards into green building certifications, the SCP creates “green” entry barriers that fundamentally alter the cost-benefit calculus of peripheral development, effectively preventing disorderly expansion.

4.4.2 Expansion of green infrastructure provision

Table 5 shows the SCP coefficient for green infrastructure is significantly positive at the 1% level. This result theoretically validates the "amenity-driven infill" hypothesis, indicating that the SCP restrains US by expanding green infrastructure, which supports Hypothesis H3. By mandating rain gardens, permeable pavements, and green roofs, the policy transforms development patterns and establishes ecological constraints that curb sprawl at its source. Consistent with spatial lock-in theories, these facilities replace grey infrastructure, reduce carbon emissions, and enhance urban resilience and livability. This mitigates the “push factors” of urban core degradation, reducing outward population dispersal and anchoring activities within existing boundaries. Additionally, integrating large-scale sponge parks into ecological red lines creates rigid physical buffers that strictly lock in the physical expansion of urban boundaries.

4.4.3 Promotion of urban polycentricity

Table 5 indicates a significantly positive coefficient (0.032) for urban polycentricity. Given the strong path dependence and slow evolution of urban spatial morphology, this statistically significant shift demonstrates that the SCP acts as an endogenous catalyst for structural reorganization, confirming Hypothesis H4. The policy sites stormwater retention hubs in suburban locations, encouraging the infrastructure-led growth of secondary centers. Consistent with the polycentric city model, this spatial decentralization restructures urban land values and commuting patterns. Supported by improved transport links, these hubs attract industrial and residential activities, relieving pressure on the primary core and curbing low-density peripheral scattering. Concurrently, sponge-based ecological corridors preserved between centers act as spatial barriers, effectively replacing the inefficient “sprawling pancake” model with a highly-ordered “multi-nodal network” morphology.

Table 5: Mechanism Verification

Variables	US	Energy utilization efficiency	Green infrastructure	Degree of urban polycentricity
SCP	-0.319***	0.081***	1.082***	0.032*
	(0.107)	(0.021)	(0.307)	(0.017)
Control variable: first-order term	YES	YES	YES	YES
Control variable: second-order term	YES	YES	YES	YES
Time fixed effect	YES	YES	YES	YES
City fixed effect	YES	YES	YES	YES
Sample size	3627	3627	3627	3627

4.5 Heterogeneity analysis

Although the preceding analysis confirms the SCP's significant restraining effect on US, its efficacy is inevitably constrained by heterogeneous initial municipal endowments. To avoid arbitrary sub-sample selection, we construct an "Institutional-Economic-Ecological" tri-dimensional framework to systematically examine how varying initial constraints moderate the policy's spatial transmission effects.

4.5.1 Institutional Capacity: Urban Hierarchy

From the perspective of institutional capacity, the SCP's spatial restructuring effect relies heavily on local fiscal strength and planning coordination. We categorize the sample into central cities (direct-administered municipalities, sub-provincial, and provincial capitals) and peripheral cities (all others). As Table 6 reports, the coefficient for central cities is significantly negative at the 1% level, while peripheral cities remain statistically insignificant. This disparity occurs because central cities enjoy higher administrative ranks, resource priorities, and severe land scarcity. These pressures encourage stricter development thresholds, equipping them with mature, enforceable planning systems that efficiently translate green investments into rigid spatial constraints. Their leading status also sets regional benchmarks. In contrast, peripheral cities suffer from weaker financial capacities and looser planning oversight, with relatively low construction land costs. Consequently, sponge projects in these contexts may sometimes be situated on low-value peripheral parcels, diluting the policy's intended restraining effect on US.

4.5.2 Economic Path Dependence: Resource Endowment

From the perspective of economic path dependence, US drivers are intrinsically linked to local economic reliance on land expansion. Since resource-abundant cities may experience the "resource curse" that diminishes environmental policy effectiveness, we divide the sample into resource-based and non-resource-based cities. Table 6 shows the coefficient for resource-based cities is negative but statistically insignificant, whereas the non-resource-based coefficient is significantly negative. This divergence arises because resource-based cities' economic lifelines depend on extensive mining and high land consumption. Their spatial morphology exhibits profound rigidity and historical path dependence, making it difficult for a single green infrastructure policy to shake the underlying inertia of sprawl. Additionally, mining-induced surface subsidence physically forces outward expansion. For these cities, industrial restructuring and social stability supersede the SCP's spatial intensification goals. Conversely, non-resource-based cities rely on manufacturing and services, offering greater elasticity for spatial restructuring. Here, SCP-mandated green infrastructure demands deliberate planning, shifting development from outward expansion toward the intensive optimization of existing urban land, thereby effectively curbing sprawl.

4.5.3 Ecological Baseline: Environmental Foundations

Regarding ecological baselines and regulatory intensity, the policy's marginal intervention effect depends on pre-existing environmental constraints. We divide the sample into key and non-key environmental-protection cities. Table 6 indicates both groups have significantly negative coefficients, yet the effect is stronger for non-key (−0.368) than key cities (−0.165). This aligns with the law of diminishing marginal returns in spatial governance: key environmental-protection cities already benefit from higher environmental investments, strict ecological red-lines, and more developed green infrastructure. Their spontaneous sprawling tendencies are largely pre-contained, inherently limiting US and reducing the SCP's marginal impact. In contrast, non-key cities start with weaker infrastructure and looser planning controls, facing fewer prior ecological constraints. Consequently, implementing the SCP in these contexts produces more pronounced and drastic marginal convergence effects on disordered urban expansion.

Table 6: Heterogeneity Analysis

Variables	Urban hierarchy		Natural endowment		Environmental Foundations	
	Central cities	Peripheral cities	Resource-based	Non-resource-based	Environmentally protected	Non-environmentally protected
SCP	-0.245***	-0.234	-0.326	-0.188**	-0.165*	-0.368*
	(0.094)	(0.149)	(0.361)	(0.082)	(0.095)	(0.204)
Control variable: first-order term	YES	YES	YES	YES	YES	YES
Control variable: second-order term	YES	YES	YES	YES	YES	YES
Time fixed effect	YES	YES	YES	YES	YES	YES
City fixed effect	YES	YES	YES	YES	YES	YES
Sample size	455	3172	1482	2145	1456	2171

5 Conclusions and Policy Recommendations

5.1 Conclusions

Against the backdrop of rapid urbanization, reconciling sustainable urban development with the containment of uncontrolled sprawl has become central to transforming the urban growth model. As a key spatial intervention aligned with the ecological civilization strategy, the SCP represents a novel pathway for integrating green infrastructure into urban morphological governance. Using a panel dataset of 279 Chinese cities from 2011 to 2023 and applying an advanced Double Machine Learning (DML) framework, this study empirically examines the causal impact of the SCP on US and its underlying spatial mechanisms. The core findings are threefold: (1) The SCP significantly restrains inefficient US, serving as an effective policy instrument for spatial containment. (2) Mechanistically, this spatial restructuring is achieved through three socio-spatial pathways: the enhancement of energy utilization efficiency, the expansion of green infrastructure provision, and the promotion of urban polycentricity. (3) The restraining effect exhibits institutional and economic heterogeneity: it is highly pronounced in central cities and non-resource-based cities, where administrative capacity and economic elasticity facilitate spatial reorganization, while being attenuated in cities with rigid resource dependence or strict pre-existing environmental baselines.

5.2 Policy Recommendations

Drawing on the empirical evidence and the framework of spatial governance, this study offers four actionable policy instruments to leverage environmental initiatives for urban morphological control:

First, institutionalize nature-based solutions as "mandatory spatial constraints" within urban master plans. Rather than treating the SCP as a flexible ecological goal, policymakers should establish binding "Green-line" boundaries for sponge infrastructure. Governments should integrate sponge-city performance metrics—such as permeable surface ratios and runoff coefficients—into the standard approval process for new land development. This transforms environmental policy from a post-hoc flood mitigation tool into a front-end regulatory barrier against low-density horizontal expansion.

Second, establish "Urban Renewal Special Funds" and tax incentives to prioritize amenity-driven infill development. To counter the fiscal reliance on peripheral land leasing, central and provincial governments should provide targeted subsidies for retrofitting existing built-up areas with micro-ecological amenities (e.g., rain gardens and green roofs). For instance, implementing tax rebates for developers who achieve specific energy-efficiency benchmarks through green infrastructure can lower the operational costs of central districts. This anchors residential and economic activities within established boundaries and reduces the fiscal incentive for suburban sprawl.

Third, deploy "Infrastructure-led Investment Packages" to foster polycentric urban networks. Strategic investments in stormwater retention hubs and large-scale sponge parks should be explicitly synchronized with Transit-Oriented Development (TOD) nodes and planned secondary centers. By providing dedicated fiscal transfers for "Sponge-TOD" integration, governments can attract high-value industries to secondary nodes, reshaping commuting patterns and preventing the "pancake-style" outward scattering of urban functions.

Fourth, implement "Hierarchical and Differentiated Fiscal Support" to address regional heterogeneity. The central government should adopt a non-universal funding sequence: For peripheral and resource-based cities, where policy effects are currently attenuated, policymakers should provide technical assistance and "transition subsidies" that link SCP construction with industrial remediation and brownfield redevelopment. For central and non-resource-based cities, focus should shift toward stringent monitoring and digital governance. Utilizing fintech and satellite-based urban analytics to track real-time spatial changes can ensure that green infrastructure effectively serves as an endogenous constraint rather than a catalyst for expansionary abuse.

5.3 Limitations and Future Research

Despite the rigorous DML framework and novel findings, this study has several limitations that chart pathways for future research. First, while fused nighttime light data effectively captures horizontal macro-urban expansion, it inherently lacks three-dimensional morphological details. Future studies could integrate high-resolution building footprint data and 3D LiDAR to assess the policy's impact on vertical sprawl and volumetric compactness. Second, this study primarily treats cities as independent observation units. Given that US and ecological systems often cross administrative boundaries, future research should incorporate spatial econometric models or Spatial DML to explore the regional spillover effects of green infrastructure investments. Finally, urban morphological transformation is a profoundly slow and path-dependent process. As the SCP continues to evolve, longitudinal studies with extended time horizons are required to continuously verify the long-term spatial lock-in effects and the life-cycle sustainability of these nature-based solutions.

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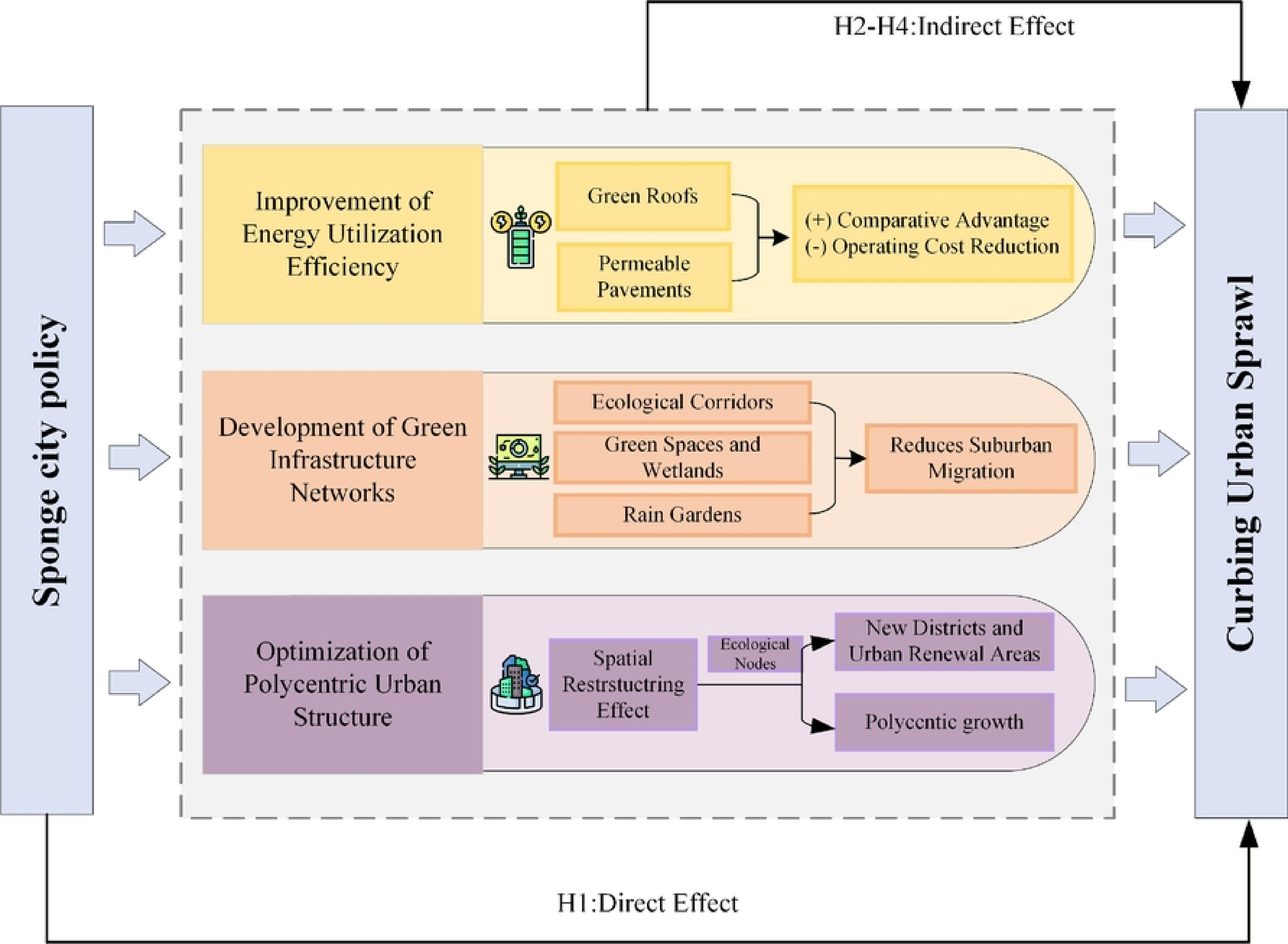
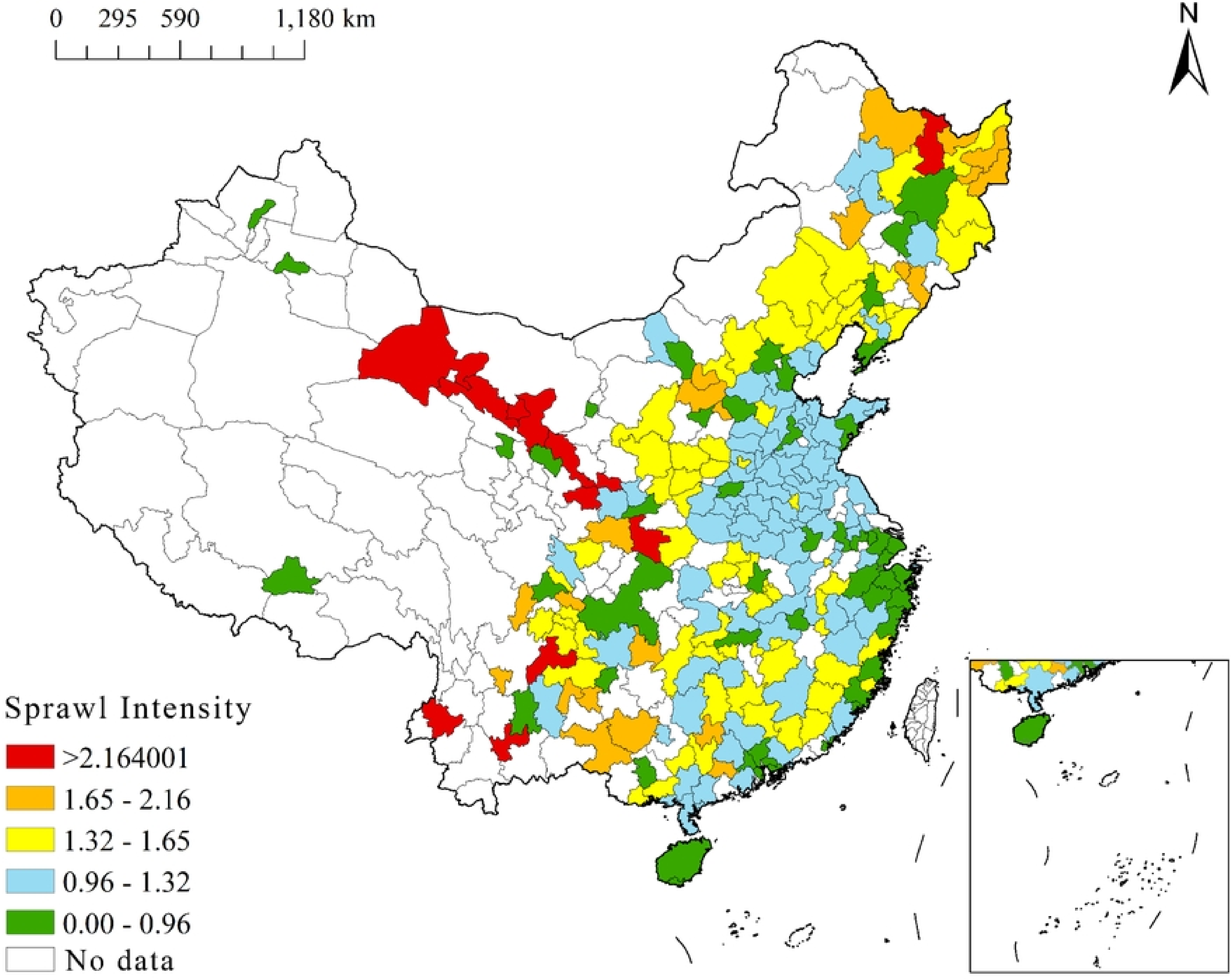

H2-H4:Indirect Effect
Sponge city policy
Improvement of Energy Utilization Efficiency
Green Roofs
Permeable Pavements
(+) Comparative Advantage
(-) Operating Cost Reduction
Development of Green Infrastructure Networks
Ecological Corridors
Green Spaces and Wetlands
Rain Gardens
Reduces Suburban Migration
Optimization of Polycentric Urban Structure
Spatial Restrstuctring Effect
Ecological Nodes
New Districts and Urban Renewal Areas
Polycentic growth
Curbing Urban Sprawl
H1:Direct Effect


0 295 590 1,180 km
N
Sprawl Intensity
>2.164001
1.65 - 2.16
1.32 - 1.65
0.96 - 1.32
0.00 - 0.96
No data