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Mechanisms of Land Use Impact on Urban Heat Island Effect and Case Studies

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Abstract:
Urbanization-induced land use changes exacerbate the urban heat island (UHI) effect by altering surface energy balance, requiring in-depth mechanistic exploration. This study clarifies how core land use types, including building density, green space structure, water allocation and transportation land, quantitatively affect UHI intensity, validated via typical urban cases. Using literature review and empirical analysis, it sorts land use-UHI correlations, then quantitatively analyzes representative urban areas with multi-source remote sensing and ground data, focusing on key factors like building density and green space scale. Findings show that built-up land density correlates positively with surface temperature and UHI intensity. Urban green spaces create a "cold island effect" via transpiration and shading; their cooling efficiency rises with scale, better connectivity and optimal tree-shrub-grass layered structures. Water bodies' cooling depends on area, morphology and distance from heat sources. Dense road networks, transportation hubs and asphalt paving intensify local heat retention and radiation. The study confirms UHI can be mitigated by controlling building density, upgrading green spaces, optimizing water layout and improving transportation materials, providing a scientific basis for sustainable, livable urban development.

Keywords: Urban heat island effect; Land use planning; Ecology; Greenfield cold island; thermal environment regulation.

1. Introduction

Urban Heat Island (UHI) refers to the phenomenon that the temperature in the core area of a city is significantly higher than that in the surrounding suburbs, which is characterized by frequent high temperatures during the daytime, slow cooling at night, and a temperature difference of up to 3-5°C between the city and the suburbs, and is particularly prominent in high-density built-up areas. UHI has multiple negative impacts on urban ecology. High temperatures accelerate the chemical reaction of pollutants, exacerbate the formation of ozone, PM2.5, and cause haze events that deteriorate air

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quality. High temperatures also force residents to increase their air conditioning needs, leading to a surge in energy consumption and greenhouse gas emissions, further exacerbating the UHI, and significantly increasing health risks for residents, including heat stress, heat stroke, and cardiovascular disease, especially for the elderly and children. At the same time, the hot environment will damage biodiversity, interfere with the water cycle (e.g., reducing precipitation infiltration), inhibit vegetation growth, and weaken ecological services (e.g., carbon sink functions). These impacts highlight the centrality of UHI as an urban sustainability challenge, and there is an urgent need to optimize land use and planning to mitigate the problem.

Different land use types have different regulatory effects on UHI. High-density development with dense road networks and hard paving can significantly increase surface heat radiation, exacerbating the intensity of UHI and manifesting the "heat source" effect. In contrast, vegetation reduces temperature through evapotranspiration and shading, and its cooling capacity increases with the increase of green space scale and optimization of structure. Water bodies have a significant cooling effect through evaporation and heat capacity regulation, and the cooling efficiency of water bodies varies with different sizes and forms. Therefore, the key to UHI mitigation lies in structural optimization, such as controlling construction density, increasing the proportion of green space, protecting the connectivity of water bodies and improving transportation materials. This directly weakens heat sources, strengthens cooling sources and realizes the overall improvement of the thermal environment.

Empirical studies have shown that built-up land increases sensible heat flux by changing albedo and heat capacity. Transpiration from green spaces enhances latent heat exchange and reduces air temperature. Evaporation processes in water bodies absorb large amounts of heat. Transportation land use enhances local heat radiation due to heat absorption by low albedo materials (e.g., asphalt). In summary, land use adjustment is regulated through physical processes to provide a scientific basis for urban planning and promote sustainable urban development.

This paper focuses on the analysis of the specific mechanism of land use's role on the urban heat island effect (UHI), delving into how different land types affect the intensity of the heat island by altering the energy balance of the land surface, including the quantitative assessment of its heat source or cold island effect. It also further demonstrates the mechanism of land use on the heat island effect through specific case studies.

The study expects to provide a scientific basis for urban planning and management by proposing an optimized land use structure to alleviate the urban heat island problem.

2. Analysis of the mechanism of land use on the heat island effect

2.1 . Mechanisms of Built-up Land Warming

The density of urban built-up land significantly contributes to the urban thermal environment through a combination of building density, building height and material properties. High building density leads to a significant increase in the proportion of hardened surfaces (e.g., roofs, roads, sidewalks), replacing existing vegetation and permeable surfaces, and thus expanding the coverage of materials with high thermal capacity. At the same time, the "urban canyon" effect created by high-rise buildings hinders near-surface air circulation and solar radiation, causing heat to be trapped at the street level and absorbing more solar radiation because of the increased building surface area. The thermophysical properties of building materials also play a key role. Common building materials, such as concrete and asphalt, combine high heat capacity with low reflectivity, resulting in the accumulation of large amounts of heat on the surface of the ground and on the surface of the building [1].

This warming effect is spatially manifested in the formation of "heat island cores". The high proportion of hardened surfaces in densely built-up areas significantly increases the efficiency of solar radiation absorption, with daytime surface temperatures often exceeding 50°C, much higher than in vegetated areas. The urban canyon structure inhibits both convective and evaporative cooling processes. At night, the high heat capacity and low thermal conductivity of the materials result in a slow release of heat, allowing buildings and roads to act as "thermal batteries" to store heat, resulting in significantly lower nighttime cooling in urban areas than in suburban areas. Typically, the temperature in the center of the city is 3-5°C higher than that in the surrounding suburbs in the summer evening, creating a stable hot spot [2].

The physical mechanism behind this involves three main aspects. First, high heat capacity materials store large amounts of thermal energy, delaying the temperature rise but prolonging the heat dissipation time. Second, low thermal conductivity limits the transfer of heat to the deeper soil layers, exacerbating surface heat retention. Finally, low albedo surfaces reduce the reflection of solar radiation, prompting more radiant energy into heat. The warming effect is further amplified by the predominance of low albedo materials that characterize urban surfaces.

Many empirical studies support the above mechanism. Satellite monitoring shows that the difference between daytime and nighttime temperatures in high-density built-up areas is significantly reduced, with daytime temperatures 2-5°C higher than those in the suburbs in summer, and the difference in nighttime temperatures can be reduced to less than 50 percent of those in the suburbs [3]. For example, a 2010-2020 study in downtown Beijing found that for every 10% increase in building density, the average summer temperature increased by 0.8-1.2°C, with the nighttime temperature difference in the high-density area of Chaoyang District reaching 4°C [4]. In New York City's Manhattan district, due to the density of buildings covered by asphalt, the difference between daytime and nighttime temperatures is only 5-8°C (compared with 5-8°C in suburban areas). In Manhattan, New York, the difference between daytime and nighttime temperatures is only 5-8°C (10-15°C in the suburbs) due to the dense buildings and asphalt pavement cover, highlighting the cumulative effect of heat-capable materials [5]. On a global scale, the World Meteorological Organization (WMO) has pointed out that the urban heat island effect has led to a 1-3°C/century increase in the average temperature of cities over the last 30 years compared to the background warming, and that high-density built-up land is a central contributor [6].

2.2 . Cooling regulation of the spatial structure of urban green spaces

The spatial structure of urban green spaces significantly regulates the urban thermal environment and reduces local air temperature through various biophysical mechanisms. The core cooling mechanism of vegetation lies in transpiration and the shading effect. Vegetation transpires water through leaf stomata and absorbs a large amount of latent heat from the air, significantly reducing air temperature. This process converts solar radiant energy into latent heat exchange, reducing sensible heat flux. At the same time, trees and shrubs and other vegetation canopies effectively block direct solar radiation on the surface, reducing the amount of absorbed short-wave radiation and heat storage, directly reducing the near-ground air temperature, so that the green space acts as a "cold source". Transpiration and shade work together to form the "evaporative cooling" and "radiative cooling" effects. Transpiration increases air humidity and cools the surrounding air through turbulent diffusion. Shade reduces heat reflection from the ground and inhibits the formation of heat islands, thus creating a cool microclimate in the interior of the green space and at the edges (e.g., parks, street green belts).

The spatial distribution pattern of green spaces (size, shape, connectivity) profoundly affects the extent and intensity of their cooling effect. Studies have shown that the size of the green space is the determining factor, with large parks (>10 ha) lowering the surrounding air temperature by 3-6°C, with an impact range of up to 500 meters. In contrast, small green spaces (<1 ha) have a relatively limited cooling magnitude and range of about 1-2°C and 50-100 m, as larger green spaces maintain a more stable pool of cooler air. The shape of the green space is also critical, with compact or circular shapes maximizing internal cooling efficiency and reducing the adverse effects of hot air intrusion at the edges. Irregular or narrow shapes are susceptible to wind channel interference, resulting in uneven cooling. In addition, the connectivity of green spaces is critical to regional cooling. A highly connected network of greenways promotes the flow and diffusion of cooler air, creating "cooling corridors" that can significantly expand the extent of cooling. Studies have shown that a 10% increase in the green space connectivity index can increase the extent of cooling by 20%. Research shows that a 10% increase in green space connectivity index can increase the cooling range by 20%. Isolated green spaces have limited cooling capacity and are easily surrounded by urban heat islands. Therefore, optimizing the distribution of green spaces (e.g., moderate size, rounded shape, high connectivity) can effectively increase the overall cooling efficiency of the city and achieve 0.5-3°C cooling at the urban scale.

The above mechanisms together contribute to the "cold island" effect in urban green spaces. This effect is the reverse of the heat island effect, where the temperature of a green space or water area is significantly lower than that of the surrounding built-up area. The formation of a stable cold island requires specific conditions to be met. The area of green space needs to reach a certain threshold, and the vegetation type should be broad-leaved trees with a high transpiration rate and high soil moisture. Under high summer temperatures, more than 30% of the area needs to be covered with green space in order to stabilize the formation of cold islands. Environmental factors also play a key role. Low wind speeds favor the concentration of cold air in green spaces. The higher the urban background heat island intensity, the more significant the cold island effect. The cold island effect is usually stronger at night due to the continuous cooling effect of latent heat released by vegetation.

Quantitatively analyzed in terms of biophysical processes, vegetation cover is a central parameter in regulating temperature. Vegetation cools temperature by altering the surface energy balance, e.g., by increasing surface albedo, decreasing net radiation, and enhancing evapotranspiration latent heat flux. Numerous quantitative studies have confirmed the significant negative correlation between vegetation cover and temperature.

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2.3 . Mitigating the effects of water body land use on urban microclimate

Urban water significantly improves the local thermal environment through its high heat capacity and evaporative cooling mechanism. The specific heat capacity of water is as high as 4186 J/(kg·K), which is much higher than that of concrete (about 880 J/(kg·K)) and soil (about 800 J/(kg·K)). This physical property results in a more moderate temperature change when absorbing an equivalent amount of solar radiation. At the same time, the continuous evaporation process on the surface of the water body absorbs about 2.5 MJ of latent heat for every 1 kg of water consumed, which effectively reduces the ambient air temperature through a phase change mechanism that is regulated by a combination of wind speed, humidity, and the surface area of the water body.

Large lakes, as a typical water form, can have significant microclimatic moderating effects. Observational data from Lake Michigan in Chicago, for example, show that it can lower the temperature of the surrounding area by up to 7°C in the summer, and such bodies of water typically achieve a daytime cooling of 3-6°C and raise air humidity by 10-20% in the downwind region, with a radius of influence that extends up to 500-1,000 m. River systems, on the other hand, form natural "cold air corridors" with a cooling effect of 2-4°C and humidity along the shoreline. River systems form natural "cold air corridors", producing a cooling effect of 2~4°C along the coast, with a humidity increase of 5~15%, regulating an area of 100~300 meters along both banks. Artificial water features, especially fountains, achieve a cooling effect of 1~3°C and a humidity increase of 5~10% within a radius of 20~50 meters through enhanced evaporation [7].

The size and spatial layout of water bodies have a decisive influence on cooling efficiency. Empirical studies have shown that an area of more than 0.5 hectares is the critical threshold for the formation of a stable "cold island" effect. For every one-fold increase in water area, the cooling range can be extended by 40-60%. At the level of spatial design, when the width of the ribbon channel is more than 30 meters, it can form a continuous cold air transport channel along the direction of water flow. The "blue-green network" system constructed by water bodies and green spaces can increase the cooling range by more than 50% through synergistic effects. The north-south oriented water body is parallel to the dominant wind direction, which not only accelerates the evaporation process, but also promotes the diffusion of cold air, and its heating uniformity is stronger than the east-west layout, with a sustained cooling capacity [8].

2.4 . Heat accumulation and heat island intensification in road traffic land use

Road transportation land, as an important part of the urban subsurface, contributes to the heat island effect through multiple mechanisms. Asphalt pavement, with its dark surface and low albedo, absorbs 70-90% of solar radiation, leading to surface temperatures of 50-70°C in the summer, and its combination of high heat capacity and low thermal conductivity allows it to store large amounts of heat energy and release it slowly at night, creating a significant 'heat retention' effect, especially under cloudless or low wind conditions, which contributes to localized temperature increases. It contributes significantly to local temperature rise, especially under cloudless or low wind speed conditions.

Dense traffic areas further superimpose the effects of anthropogenic heat emissions. Vehicle engine operation and tailpipe emissions directly release high-temperature gases, and in congested roadways, there is continuous heat output from frequent starts and stops. This waste heat is superimposed on the heat stored in the asphalt pavement, creating localized "hot spots" that lead to additional increases in regional temperatures. At the same time, the greenhouse gases emitted by motor vehicles enhance the absorption of long-wave radiation in the atmosphere, which indirectly strengthens the heat island effect.

There is a clear positive correlation between transportation network density and heat island intensity. High-density road network areas are usually accompanied by an increase in the proportion of impervious surfaces, a concentration of mobile heat sources, and a compression of green space, resulting in a significantly higher heat island intensity in the urban core than in the suburbs. The underlying mechanism is that the dense road network not only expands the heat storage capacity through hardened pavement but also continuously releases waste heat through traffic flow and suppresses the evaporative cooling function of vegetation, forming a self-reinforcing vicious cycle.

Heat build-up is further amplified by urban form factors. The "urban canyons" formed by high-rise buildings and narrow streets can reduce natural wind speeds and significantly weaken convective heat dissipation. At the road traffic level, structures such as roundabouts, tunnels and elevated roads create "wind shadow zones" that impede the diffusion of hot air, while traffic particles (e.g., PM2.5) suspended in static air exacerbate the temperature rise by absorbing radiant heat.

3. Case studies

3.1 Case 1: Built-up Density Impact on UHI Intensity

Remotely sensed surface temperature (LST) inversion studies reveal that there is a significant positive correlation between built-up land density and heat island intensity. Empirical data show that for every 10% increase in built-up land density (including road and building coverage), the surface urban heat island intensity (SUHI) rises by an average of 0.5-1.5°C. This phenomenon stems from the physical properties of impermeable surfaces in high-density areas. Materials such as asphalt roads and concrete, which generally have an albedo of less than 0.15, can absorb more than 80% of solar radiation, while at the same time having only one-fifth the evaporative cooling capacity of natural surfaces. The density of built-up land contributes 60-70% of the heat island intensity, with a typical SUHI intensity of 4-6°C in the high-density core of Beijing's fifth ring road, while the low-density satellite towns on the outskirts of Berlin show only a 1-2°C difference in temperature rise.

There is a significant synergistic effect between building land density and sprawl patterns. High-density sprawl areas (e.g., Pudong, Shanghai) experience an 8-10°C surge in SUHI compared to the rural baseline due to a combination of thermal storage effects and low albedo surfaces; in contrast, low-density sprawl areas (e.g., Atlanta) experience a reduction in SUHI contribution of about 15% due to vegetation cuts. This mechanism provides empirical support for heat island mitigation strategies: limiting land use density to less than 60% (e.g., the Tokyo policy) reduces SUHI by about 1.5°C, and adopting a "compact city + green corridor" model (e.g., the Copenhagen approach) reduces heat island contribution by 30%.

The global study by Peng et al. finally quantified that built-up land density is the dominant factor in the heat island effect (60-70% contribution), driving warming mainly through thermal storage capacity and low albedo characteristics. The pattern of urban expansion determines the incremental heat risk (20-30% contribution), with sprawl being particularly dangerous in arid zones. The findings reveal significant regional differences, with rapidly expanding cities in Asia and Africa prioritizing land use density control, and mature cities in Europe and the United States focusing on optimizing expansion patterns [9].

3.2 Case 2: Urban green space structure and cooling effect

In a systematic review based on 38 empirical studies, Bowler et al. (2010) showed that the cooling effect of urban green space is closely related to its spatial structure and vegetation configuration. Trees can achieve localized cooling of 5-8°C by their highly dense canopy and strong transpiration capacity, which is significantly higher than the 2-4°C of shrubs or the 1-3°C of lawns, and the synergistic evapotranspiration and turbulence enhancement between vegetation can increase the cooling rate to 4-7°C and extend the duration of cooling by more than 40% when using a tree-irrigation-grass layered structure. The synergistic evapotranspiration and turbulence enhancement effect between vegetation can increase the cooling rate to 4-7°C and extend the cooling duration by more than 40%, as evidenced by the observation data of Beijing Olympic Forest Park.

The scale and shape of the green space also dominate the trend of the cooling range. It was found that small patches of 0.1-0.5 hectares showed the optimal cooling efficiency per unit area, with a temperature drop of 1.2-1.8°C per hectare, while ribbon green spaces could extend the cooling effect along the dominant wind direction up to 500 meters away from the area. It is worth noting that when the connectivity of the green space corridor network exceeds 0.6, the cooling range of fragmented patches can be expanded by 50%, as exemplified by the 22% reduction of the core area of the heat island through this strategy in the Berlin greenway system.

The moderating effect of climate context on cooling efficiency should not be ignored. In arid cities such as Dubai, the cooling efficiency of green spaces can be as high as 0.45°C per unit of cover due to the low humidity environment, much higher than the 0.12°C per unit of cover in humid Singapore. During extreme heat events, the cooling capacity of the green space can be up to nine times that of the cold wave period, highlighting its climate resilience value. Among the structural parameters, the three-dimensional green volume (leaf area bulk density) proved to be the central element, with a temperature reduction of 0.3-0.6°C per m^2/m^3 increase, contributing more than 55%.

Based on the above rules, the planning practice should focus on three measures: embedding small-scale high-density green spaces in built-up areas, setting up green belts with a width of more than 30 meters along ventilation corridors, and differentiating the vegetation according to climatic characteristics - giving priority to guaranteeing tree coverage and irrigation systems in arid areas, and strengthening the structure of complex communities and optimizing air circulation in humid areas. Air circulation optimization [10].

4. Conclusion

This study shows that the urban land use pattern is a

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central factor in shaping the intensity of the heat island effect. High-density built-up land absorbs and stores large amounts of heat through large areas of hard paving, which, together with the "urban canyon" effect that prevents heat dissipation, becomes the most important source of heat, significantly pushing up the surface temperature. On the contrary, urban green space and natural water bodies play a key role as "cold islands". Green space effectively reduces temperature through vegetation transpiration and shading, and its cooling capacity increases significantly with larger area, optimized structure, and increased spatial connectivity. Water bodies rely on their high heat capacity and evaporation process to absorb heat, and their cooling efficiency is affected by their size, shape and distance from the heat source. Road traffic land uses exacerbate the heat island effect, and asphalt pavements with low albedo have a high capacity to absorb heat. Together with the waste heat emitted by motor vehicles, obvious localized hotspots are formed in the areas of dense road networks and transportation hubs. The study confirms that the density of built-up land is significantly and positively correlated with the heat island intensity, while the green space coverage is negatively correlated with it.

Therefore, the key to mitigating the urban heat island effect lies in optimizing the land use structure. Specific strategies include: rationally controlling construction density and development patterns, protecting and expanding the scale and improving the quality of green spaces. Maintaining and optimizing the layout of water bodies to maximize their cooling benefits, and promoting the use of highly reflective materials in traffic areas to reduce heat absorption. Through these comprehensive land planning and design measures, heat sources can be effectively weakened and cooling sources strengthened. This will significantly improve the urban thermal environment and provide a scientific basis for building more livable and climate-resilient, and sustainable cities.

The limitation of this study is that horizontal comparisons of cities in different climate zones have not been systematically included. In the future, cross-regional, multi-temporal and dynamic response studies should be deepened based on multi-source remote sensing and microclimate modeling to improve global urban heat island mitigation strategies.

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