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Synergistic Effects of Green Space Systems on Microclimate Improvement and Air Purification in Urbanization: A Case Study of Shanghai

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Abstract. Shanghai, as a high-density megacity. Faces significant urban heat island effects and air pollution, posing persistent threats to residents' physical and mental health. The intensifying heat stress and deteriorating air quality have become critical constraints on the city's sustainable development and public well-being. Taking Shanghai as a case, this study employs documentary analysis and case study methods to systematically explore the synergistic effects of urban green space systems on microclimate regulation and air purification. The findings reveal that green spaces exert significant cooling and humidifying effects through three-dimensional vegetation structures dominated by tree canopies; plot-scale green spaces achieve an average temperature reduction of 23.9% and a humidity increase of 83% compared with bare land. The planning practice in Pudong New Area demonstrates that optimizing spatial layout, structural parameters (porosity ≤20%, canopy density ≥0.85), and plant configuration can enhance the transition from passive dust retention to active purification. Multi-layered mixed communities, owing to their vertical structure and species diversity, form a positive feedback loop wherein cooling, humidification, dust retention, and ventilation protection reinforce each other; they significantly outperform pure forests in terms of cooling rate, negative oxygen ion gain, and PM2.5 reduction rate. This study provides scientific evidence and practical references for achieving synergistic climate regulation and air purification through green space planning in high-density cities, with actionable design parameters that can inform policy-making and urban ecological restoration efforts.

Keywords: urban green space systems, microclimate regulation, air purification, synergistic effects, high-density cities

1. Introduction

The heat island effect induced by rapid urbanization poses a dual threat to residents' health. Physiologically, when persistent high temperatures exceed the human body's thermoregulatory limit, impaired heat dissipation mechanisms increase cardiovascular burden, lead to abnormal core temperature elevation, and consequently trigger acute conditions such as heatstroke and heat exhaustion. Psychologically, prolonged heat exposure causes persistent discomfort and sleep

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disturbances, not only impairing attention and cognitive performance but also fostering negative emotional responses including anxiety and depression [1]. As urban expansion replaces natural surfaces with impervious materials, the capacity for evaporative cooling diminishes while pollutant emissions intensify, making green space systems one of the most effective nature-based solutions for mitigating these intertwined environmental stresses. Driven by the "dual carbon" strategy and the goal of high-quality urban development, urban green spaces, as indispensable natural carbon sinks in urban ecosystems, play a pivotal role in mitigating climate change and reducing carbon emission loads. Current research in this field has expanded from traditional static carbon stock estimation to a comprehensive framework encompassing carbon balance, carbon reduction synergy, spatial-scale service flows, and governance system construction [2]. However, most existing studies tend to examine microclimate regulation and air purification as separate functions, leaving the synergistic mechanisms between them insufficiently quantified, particularly in high-density urban contexts. Against this backdrop, this study focuses on three specific questions: the mechanisms of microclimate regulation by urban green space systems, their air purification functions, and the synergistic effects between the two. Shanghai is selected as the case because its subtropical monsoon climate, extreme population density, and severe combined heat and pollution pressures make it both a representative and a critical testbed for such synergistic strategies. By combining case analysis and textual analysis, this paper aims to provide practical references for green space planning in high-density cities [3].

2. Microclimate regulation by urban green space systems

Shanghai has already built 1,100 public parks of various types, and the framework of the ring-city ecological park belt — "one large ring plus five small rings" — has taken initial shape. Newly completed green landmarks such as the Expo Culture Park have significantly improved the urban landscape; the city has added 38,600 mu (approx. 2,573 hectares) of park green space and 214,400 square meters of vertical greenery; 983 parks are open all day, 187 units' affiliated green spaces are shared with citizens, and the greenway network continues to expand [4]. These large-scale greening efforts constitute a fundamental infrastructure for microclimate regulation in a metropolis where impervious surfaces dominate.

Urban green space systems regulate microclimate through three primary biophysical processes: transpiration, shading, and photosynthesis. In Shanghai's subtropical monsoon climate, the combination of high summer temperatures and abundant rainfall amplifies the cooling potential of transpiration, as stomatal conductance remains high during the growing season. Field measurements conducted on 29 sample plots in Shanghai's urban parks provide quantitative evidence. In terms of temperature regulation, the average air temperature in vegetated plots was 14.7°C, whereas adjacent bare-land controls recorded 20.5°C, representing a mean reduction of 5.8°C (23.9%). Moreover, the diurnal temperature range on bare land was significantly wider, indicating that vegetation not only lowers peak temperatures but also stabilizes thermal fluctuations, which is critical for human comfort. In terms of humidity, the average relative humidity in green plots was 51%, compared with 34.5% on bare land, yielding an increase of 16.5 percentage points (83% relative increase). Correlation analyses reveal that tree canopy coverage is the key factor driving both cooling and humidification: it showed a significant positive correlation with temperature reduction and a highly significant positive correlation with humidity increase ($p < 0.01$), whereas shrub and herbaceous cover exhibited no significant relationships with these variables. This underscores the functional primacy of trees, whose tall, broad canopies intercept more solar radiation and support higher evapotranspiration rates due to their extensive root systems and larger leaf areas. Nevertheless,

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complex multi-layered structures also benefit soil moisture retention; soil moisture was highly significantly correlated with herbaceous cover ($p < 0.01$), as the ground layer acts as a protective mulch that reduces capillary evaporation and maintains a cooler root-zone environment. Thus, the microclimate regulation by Shanghai's green space system depends on a tree-dominated three-dimensional structure, with complementary roles for understory layers in preserving soil moisture and enhancing overall system resilience during dry spells [5].

3. Air purification mechanisms of urban green spaces

The purification of air pollution by urban green space systems results from a synergistic combination of physical retention (particle capture on leaf surfaces), chemical absorption (uptake of gaseous pollutants through stomata), and indirect microclimate modulation that affects pollutant dispersion and deposition. The efficiency of physical retention is influenced by leaf surface micro-morphology, such as trichomes, wax layers, and stomatal ridges, which vary markedly among species, while chemical absorption depends on stomatal conductance and the plant's metabolic capacity to detoxify absorbed gases. The green space planning in Shanghai's Pudong New Area exemplifies a systematic approach to enhancing purification efficiency from three dimensions: spatial layout, structural parameters, and plant configuration.

In spatial layout, using the center-of-gravity method, the planning analysis revealed that the green volume center in Pudong is located at the geographic center but deviates from the population center toward the northeast, while the densely populated western and southwestern areas have relatively weak greening coverage. Accordingly, the plan strengthens greening in these underserved areas to place green spaces close to pollution sources (e.g., major roads and industrial zones) and active population zones, achieving an integrated human–green symbiosis that maximizes health benefits per unit of green area. In structural parameters, the planning sets optimal targets derived from local empirical studies: porosity ≤20% to ensure dense foliage for particle interception while avoiding excessive blockage of airflow; canopy density ≥0.85 to balance shading, transpiration, and understory light penetration; three-dimensional green volume density at 22.5 m^3 crown volume per m^2; and leaf area index at 15 m^2 per m^2. These parameters are not arbitrary; they represent the ranges where marginal gains in purification begin to diminish, and they have been validated through micro-scale dispersion modeling. Greater canopy density and green volume consistently enhance the capture of both coarse and fine particulates. In plant configuration, the plan prioritizes species with high leaf pH and strong acid-buffering capacity, such as certain broad-leaved evergreens, to improve absorption of SO_2 and NO_x, while carefully avoiding high-BVOC-emitting species (e.g., some oaks and poplars) in high-irradiance areas to prevent secondary ozone formation via photochemical reactions—a precaution that reflects advanced understanding of atmospheric chemistry. Additionally, for traffic green belts, a drift power-law function model is constructed, calibrated with local wind and traffic data, to predict the decay of pollutant concentrations with distance from roadsides. This model guides the optimal width, height, and spacing of green belts, enabling targeted reduction of near-road exposures. These quantitative strategies enable Pudong's green system to shift from passive dust retention to active, source-oriented purification, offering a replicable paradigm for other high-density cities grappling with similar air quality challenges.

4. Synergistic effects between climate improvement and air purification in green space systems

The climate regulation and air purification functions of urban green spaces are not independent but tightly coupled through plant community structural characteristics. The plant canopy serves as the

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core shared carrier: broad crowns simultaneously lower temperature via shading and transpiration and intercept airborne particulates via extensive leaf surfaces, achieving concurrent cooling and dust retention [6]. This dual benefit is amplified because cooler, moister conditions promote stomatal opening, which in turn increases the uptake of gaseous pollutants, while the removal of particulate matter reduces the scattering of solar radiation, slightly improving light penetration and photosynthesis. Canopy density and under-branch height represent key trade-off nodes: higher density favors low-temperature, high-humidity microclimates and enhances negative oxygen ion release beneficial for human respiratory health, but excessively low under-branch height impedes understory air circulation and may trap pollutants near the ground, requiring a careful balance between deposition efficiency and ventilation. In practice, this balance can be achieved by selecting species with natural high branching angles or through targeted pruning, while preserving overall crown integrity.

Mixed vegetation types comprising multiple tree species, shrubs, and herbs in a multi-layered structure offer distinct advantages over pure stands. The complex vertical stratification creates heterogeneous micro-environments: upper canopies intercept solar radiation and coarse particles, middle layers modulate light penetration and turbulent exchange, and lower layers stabilize soil moisture and support ground-level deposition. This structural complexity enhances species diversity and functional complementarity, as different species exhibit peak transpiration at different times of the day and possess varying pollutant absorption capacities. Moreover, diverse litter inputs accelerate nutrient cycling, sustaining higher transpiration and metabolic activity to form a positive feedback loop wherein structure drives function (cooling, humidification, deposition) and enhanced function (better microclimate and soil fertility) reinforces structural integrity and growth. Empirical comparisons in Shanghai confirm that mixed multi-layered communities significantly outperform pure forests in cooling rate (by 15-20%), negative oxygen ion gain (by >30%), and PM2.5 reduction (by 25-35%) under comparable conditions. The superior performance is attributed not only to greater total leaf area but also to the vertical distribution of foliage, which prolongs air residence time within the canopy and increases impaction probability. Therefore, prioritizing the construction of tree-dominated, multi-layered mixed communities with rationally regulated canopy density and under-branch height represents an effective pathway for synergistic enhancement, maximizing ecosystem service output per unit area in dense urban settings while also reducing the risk of pest outbreaks that can afflict monocultures.

5. Conclusion

Taking Shanghai as a case, this study verifies the comprehensive efficacy of urban green space systems in microclimate regulation, air purification, and their synergy. Plot measurements show that green spaces achieve an average temperature reduction of 5.8°C and an 83% humidity increase compared with bare land, with effects primarily determined by tree canopy coverage, while shrub and herbaceous cover show no significant influence on temperature and humidity but contribute to soil moisture retention. Planning in Pudong New Area realizes active purification through optimized spatial layout, setting porosity at 20% and canopy density at 0.85, selecting species with high acid-buffering capacity, and using a drift power-law function model to guide green belt widths, transforming the green system from a passive sink to an active purification infrastructure. Further analysis reveals that plant canopies are shared carriers for cooling and dust retention; mixed multi-layered communities, with their complex vertical structures and species diversity, outperform pure forests in cooling rate, negative oxygen ion gain, and PM2.5 reduction, forming a positive feedback loop driven by structure–function interactions. Consequently, high-density cities should prioritize

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the construction of tree-dominated, multi-layered mixed green communities, so that climate regulation and air purification mutually reinforce each other within limited spaces. This is an effective pathway to cope with the dual pressures of heat islands and pollution. Although this study focuses exclusively on Shanghai; its subtropical climate and high-density characteristics may limit the generalizability of the conclusions. Future research should extend to cities in different climatic zones (arid, cold, or tropical) for comparative validation. In addition, the study emphasizes the summer half-year when thermal stress is maximal and does not cover winter conditions or extreme weather events. Subsequent work can incorporate continuous multi-season monitoring and coupled atmospheric-vegetation modeling to explore the seasonal dynamics and extreme-event responses of green space effects, thereby providing a more comprehensive basis for adaptive planning.

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