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The impact of residential green spaces on urban air humidity regulation in traffic-influenced urban environments

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ABSTRACT

Urban green spaces represent an important factor in mitigating the negative environmental consequences of intensive urbanization, particularly in regulating microclimatic conditions. Their significance is most commonly observed through the mitigation of the urban heat island effect, primarily by shading heat-absorbing surfaces and driving ecohydrological processes such as evapotranspiration. However, beyond temperature-related effects, increasing attention is being given to the role of urban green spaces in regulating atmospheric humidity, an essential yet insufficiently researched microclimatic parameter. Traffic corridors represent a major source of environmental degradation in cities, where extensive asphalt surfaces intensify urban overheating. Owing to their strategic spatial positioning along these corridors, residential green spaces may play a crucial role in buffering microclimatic extremes and enhancing urban bioclimatic comfort. This study evaluates the hypothesis that residential green spaces exerts a positive impact on local air humidity, with the magnitude of this effect conditioned by vegetative cover, dendrological structure, and spatial extent. The research was conducted across five residential green spaces along high-density traffic corridors in New Belgrade. The empirical findings reveal that green spaces ranging from 0.7 to 1.4 ha consistently enrich relative air humidity by enhancing local atmospheric moisture fluxes within the urban canopy layer by 0.4% to 3.7% in their immediate surroundings. Furthermore, the magnitude of humidity regulation is strongly governed by dendrological structure and vegetation cover, rather than scaling linearly with total green space area. Ultimately, the results of this study provide practical guidelines for improving the planning, design, and management of residential green infrastructure in the context of urban climate change adaptation.

Keywords: air humidity, ecohydrology, evapotranspiration, green infrastructure, urban climate adaptation, urban water cycle, landscape engineering.

INTRODUCTION

Green spaces represent crucial structural components of the urban landscape that directly enhance environmental quality and human well-being by mitigating microclimatic degradation. Built-up surfaces and dark asphalt corridors absorb and re-emit vast amounts of thermal energy, intensifying the Urban Heat Island (UHI) effect and severely reducing near-ground air humidity along heavily trafficked arteries (Taha, 1997). Vegetation integrated within these spaces mitigates such adverse conditions by regulating urban microclimates, attenuating temperature extremes, and elevating relative air humidity through an oasis effect operating at both macro and micro levels (Wilmers, 1988; Chen and Wong, 2006; Stojanović, 2016; Kecman et al., 2025).

Evapotranspiration represents a fundamental component of the urban hydrological cycle,

driving the vertical movement of water from the soil-vegetation system into the atmosphere (Givoni, 1991; Kimura, 1991). As a key ecohydrological process, transpiration enables plants to absorb soil water and release it as water vapor, directly modifying atmospheric moisture flux within the near-ground boundary layer. In urban environments, this near-ground layer represents the urban canopy layer (UCL), which extends from the ground up to average canopy and roof height. The intensity of this hydrological process is governed by the leaf area index (LAI), canopy closure, and vegetation density. By continuously releasing water vapor into the atmosphere, plant material elevates relative humidity levels while simultaneously generating a cooling effect through evapotranspirative cooling and solar shading. Even at small scales, the magnitude of this bioclimatic effect in ecologically degraded urban environments depends on a wide range of factors, including the size and dendrological structure of the green space, season, time of day, and prevailing local meteorological conditions (Spronken-Smith and Oke, 1998; Upmanis and Chen, 1999). Thus, the synergy of these ecohydrological processes establishes distinct microclimatic gradients between vegetated spaces and artificial or asphalt-covered surfaces.

Numerous studies worldwide confirm the significant impact of urban green spaces, particularly large-scale categories such as urban parks and forests, on modifying urban thermal regimes (Hamada and Ohta, 2010; Oliveira et al., 2011; Stojanović et al., 2018; Kraemer and Kabisch, 2022; Xiao et al., 2022; Haeffelin et al., 2024). However, in addition to large parks, residential green spaces play an equally vital role in improving environmental quality. Previous research often fails to capture how residential block green belts, operating under heavy anthropogenic traffic loads, trap, retain, and redistribute airborne water vapor within the UCL.

Addressing these research gaps, this study provides empirical evidence of the vital ecohydrological role of residential green spaces in regulating air humidity along major traffic corridors in New Belgrade, Serbia, a planned urban environment characterized by open-block geometry and heavy vehicular traffic. This research focuses on the UCL across the analyzed open-block structures of New Belgrade, where microclimatic buffering and transpirational vapor retention directly occur. By shifting the analytical focus from macro-scale cooling to localized atmospheric humidification, this research evaluates relative air humidity as a fundamental, highly dynamic ecohydrological indicator of urban ecosystem functionality (Amani-Beni et al., 2018; Stojanović et al., 2021; Du et al., 2021; Li et al., 2025).

The novel contribution of this study lies in evaluating the capacity of residential greenery to increase air humidity and improve local microclimates through a combination of paired micro-spatial sampling, multi-year empirical field validation, and ecohydrological attribute integration. Rather than relying on single-point readings or idealized numerical modeling and software simulations, this work measures continuous moisture gradients directly across road-facing and residential-facing sides of block vegetation barriers under actual traffic stress. By doing so, it provides long-term empirical evidence of how green barriers trap, retain, and elevate atmospheric humidity, while directly linking these microclimatic benefits to canopy structural parameters and functional foliar characteristics. The ultimate objective of this work is to provide actionable ecohydrological guidelines for the climate-resilient planning, design, and long-term management of residential green infrastructure in modern urban environments.

METHODOLOGY

The study is based on the hypothesis that residential greenery, particularly that located along traffic corridors, exerts a continuous, statistically significant positive impact on local atmospheric humidity. The investigation into the effects of residential greenery on the regulation of surrounding air humidity was based on systematic monitoring and measurement of relative air humidity, as an indicator of atmospheric moisture dynamics, across selected residential green spaces located along major traffic corridors in New Belgrade. The study sites were selected according to three main criteria:

- Green space category: The selected sites belong specifically to the category of residential block greenery, defined as vegetated areas, groups, or masses of vegetation located within a single residential green spaces (Anastasijević and Anastasijević, 2012).
- Spatial positioning: Due to their location relative to the adjacent road network, each site functions as a protective ecohydrological green belt extending along the roadway, situated between the traffic corridor and residential structures.

- Accessibility and field suitability: Selected sites allowed for continuous, long-term atmospheric moisture and microclimatic measurements without physical or operational disruptions.

Based on these criteria, five residential green spaces were selected along four primary traffic corridors in New Belgrade: the international E-75 highway corridor, Mihajlo Pupin Boulevard, Nikola Tesla Boulevard, and Tošin Bunar Street. Measurements were taken at two distinct sampling positions at each site: behind the green space (H_1, facing the residential complex) and in front of the green space (H_2, facing the traffic corridor).

The vegetation cover, dendrological structure, and site characteristics of the investigated green spaces are detailed in Table 1.

Vegetation cover is expressed as the percentage share of different functional plant groups (trees, tree-shrub combinations, shrubs, and turfgrass) as well as impervious/paved surfaces relative to the total site area.

Air humidity was measured over two consecutive calendar years during the spring, summer, and autumn seasons. Measurements were organized in three annual series, each consisting of two consecutive daily measurements. A total of 36 measurements were taken per site (18 measurements per year, with six measurements per season). Data collection was conducted using two calibrated digital meteorological stations with an operational measurement range for relative humidity (RH) of 25% to 95% and a resolution of 0.1%.

To eliminate boundary interference and localized thermal distortion, measuring positions behind the green spaces were located at a sufficient distance from residential buildings to prevent feedback effects such as building surface radiation, thermal mass emission, or unwanted shading. All measurements were conducted during morning hours at a standardized operational height of 130 cm above ground level (Georgi and Dimitriou, 2010) at fixed time intervals throughout the monitoring period. At each sampling point, air humidity values were recorded five minutes after activating the instruments to allow sensor stabilization.

The influence of residential green spaces on air humidity modification (H_r), representing the spatial atmospheric moisture gradient generated by the vegetation barrier, was calculated as the difference between the mean relative humidity values measured behind (H_1) and in front of (H_1) the green space:

$$\begin{gathered} H_r = H_1 - H_2 \\ H_r = H_1 - H_2 \\ H_{r\ avg\ tot} = H_{1\ avg\ tot} - H_{2\ avg\ tot} \end{gathered} \quad (1)$$

The paired-samples *t*-test was used to determine whether there were statistically significant differences in air humidity values between $H_{1\ avg}$ and $H_{1\ avg}$:

$$t = \frac{H_{r\ avg}}{\frac{S}{\sqrt{N}}} \quad (2)$$

where: $H_{1\ avg}$ – seasonal mean relative air humidity behind the green space (residential side), calculated for each season (spring, summer, autumn) across the two analyzed years (%); $H_{1\ avg}$ – seasonal mean relative air humidity in front of the green space (traffic side), calculated for each season (spring, summer, autumn) across the two analyzed years (%); $H_{r,avg}$ – seasonal mean relative humidity difference, representing the spatial moisture gradient generated by the green space for a given season across the two analyzed years (%); $H_{i\ avg\ tot}$ *(i=1,2,r)* – total overall mean relative air humidity behind the green space (residential side) ($H_{1avg\ tot}$) and in front of the green space (traffic side) ($H_{2avg\ tot}$), calculated across all combined seasons over the two-year period (%); S – the standard deviation of the differences, and *N* –the total number of paired observations.

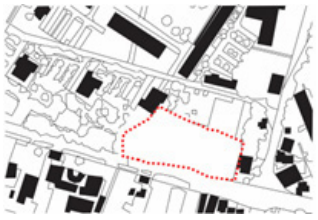
Statistical significance of the differences between these paired mean values was evaluated to determine the ecohydrological regulatory effect of the greenery. The magnitude of the effect exerted by the green spaces on atmospheric humidity was quantified using the eta squared metric (η^2). The eta squared value for the paired-samples *t*-test was calculated as follows:

$$\eta^2 = \frac{t^2}{t^2 + (N-1)} \quad (3)$$

where: *t* is the calculated t-statistic value and *N* is the total number of paired observations.

Effect sizes were interpreted according to standard thresholds established by Cohen (1988):

Table 1. Cover, dendrological structure, and appearance of residential green spaces

BLOCK 1		**Dendrological structure:** *Acer platanoides* L., *Acer pseudoplatanus* L., *Berberis vulgaris* L., *Cercis siliquastrum* L., *Celtis occidentalis* L., *Cotoneaster zabelii* C.K.Schneid., *Corylus colurna* L., *Fraxinus pennsylvanica* Marshall., *Hibiscus syriacus* L., *Koelreuteria paniculata* Laxm., *Philadelphus coronarius* L., *Pinus nigra* J.F.Arnold and *Populus alba* L. **Green space area:** 1.2 ha; **Green space cover:** trees 46.63 %; trees and shrubs 53.37 %; shrubs 0 %; lawns 0 %; pavement 0 %;	
BLOCK 2		**Dendrological structure:** *Acer ginnala* Maxim., *Acer pseudoplatanus* L., *Berberis vulgaris* L., *Betula pendula* Roth, *Prunus cerasifera* ‚Atropurpurea', *Prunus laurocerasus* L., *Pseudotsuga menziesii* (Mirb.) Franco, *Pyracantha coccinea* M.Roem., *Salix alba* L., *Syringa vulgaris* L. and *Tilia tomentosa* Moench. **Green space area:** 0.7 ha; **Green space cover:** trees 16.31 %; trees and shrubs 64.21 %; shrubs 0 %; lawns 6.68 %; pavement 12.80 %;	
BLOCK 3		**Dendrological structure:** *Betula pendula* Roth, *Carpinus betulus* L., *Celtis occidentalis* L., *Corylus colurna* L., *Cotoneaster horizontalis* Decne., *Forsythia ×intermedia* Zabel, *Forsythia suspensa* (Thunb.) Vahl, *Ligustrum ovalifolium* Hassk., *Magnolia ×soulangeana* Soul.-Bod., *Platanus ×acerifolia* (Aiton) Willd., *Pinus nigra* J.F.Arnold, *Pinus strobus* L., *Spiraea ×vanhouttei* (Briot) Carrière. **Green space area:** 1.4 ha; **Green space cover:** trees 21.19 %;trees and shrubs 19.05 %; shrubs 3.39 %; lawns 22.75 %; pavement 33.62 %;	
BLOCK 4		**Dendrological structure:** *Acer saccharinum* L., *Cedrus atlantica* (Endl.) G.Manetti ex Carrière, *Cedrus deodara* (Roxb. ex D.Don) G.Don, *Juglans regia* L., *Koelreuteria paniculata* Laxm., *Philadelphus coronarius* L., *Platanus ×acerifolia* (Aiton) Willd., *Tamarix tetrandra* Pall. ex M.Bieb., *Robinia pseudoacacia* L., *Tilia ×euchlora* K.Koch, *Tilia tomentosa* Moench. **Green space area:** 1.2 ha; **Green space cover:** trees 14.20 %; trees and shrubs 31.62 %; shrubs 0 %; lawns 20.20 %; pavement 33.98 %;	
BLOCK 5		**Dendrological structure:** *Acer negundo* L., *Acer pseudoplatanus* ‚Atropurpureum', *Gleditsia triacanthos* L., *Populus alba* L., *Populus simonii* Carrière, *Prunus cerasifera* Ehrh., *Ulmus laevis* Pall., *Ulmus pumila* L. **Green space area:** 0.7 ha; **Green space cover:** trees 51.55 %; trees and shrubs 0 %; shrubs 0 %; lawns 31.10 %; pavement 17.35 %;	

small effect (η^2 = 0.01), moderate effect (η^2 = 0.06), and large effect (η^2 = 0.14).

Statistical analyses were performed using SPSS version 20. The null hypothesis (H_0) assumed no statistically significant difference between the mean air humidity values recorded behind and in front of the investigated green spaces ($p > 0.05$).

Furthermore, the relationship between air humidity regulation and green space characteristics was analyzed in relation to spatial and structural parameters:

- Vegetation cover and spatial extent: Spatial boundaries, site surface area, and proportional land cover (trees, trees and shrubs, shrubs, turfgrass, and paved surfaces) were determined using georeferenced aerial photographs processed in MapInfo Professional 10.
- Botanical nomenclature was standardized according to *Flora Europaea* (Tutin et al., 1964–1980) and the GRIN Taxonomy database (Wiersema, 2019).

RESULTS

The empirical measurements of relative air humidity recorded behind (H_1, residential-facing side) and in front of (H_2, road-facing side) the 5 sample residential green spaces are summarized

in Table 2, while the seasonal and the total average values of air humidity in the analysed residential green spaces are summarized in Table 3. The spatial distribution of the findings is also graphically presented in Figure 1.

Across all studied residential blocks, a positive spatial moisture gradient was consistently established, characterized by significantly higher relative humidity levels on the sheltered residential side (H_1) compared to the exposed traffic corridor (H_2). This spatial gradient reflects the localized ecohydrological moisture enrichment induced by plant evapotranspiration and canopy water vapor retention:

Table 2. Air humidity measurements in 5 sample residential green spaces (blocks) H_1– air humidity behind the green space (%); H_2 – air humidity in front of the green space (%); H_r – relative humidity difference ($H_r = H_1 - H_2$).

Specification			BLOCK 1			BLOCK 2			BLOCK 3			BLOCK 4			BLOCK 5		
			H_1 (%)	H_2 (%)	H_r (%)	H_1 (%)	H_2 (%)	H_r (%)	H_1 (%)	H_2 (%)	H_r (%)	H_1 (%)	H_2 (%)	H_r (%)	H_1 (%)	H_2 (%)	H_r (%)
SPRING	I year	1. measuring	41.2	39.9	1.3	30.2	29.4	0.8	27.9	26.2	1.7	26.6	24.5	2.1	31.8	29.6	2.2
			40.6	39.6	1	31.1	30.2	0.9	27.5	25.9	1.6	26.5	24.7	1.8	31.6	29.6	2
		2. measuring	32.9	31.6	1.3	34.7	33	1.7	38.9	37.6	1.3	29.9	28.5	1.4	35.8	34.5	1.3
			33.7	32.1	1.6	35.4	33.8	1.6	38.9	37.8	1.1	29.5	28	1.5	36.2	34.5	1.7
		3. measuring	34.8	33.7	1.1	38.6	37	1.6	34.7	33.7	1	34.8	32	2.8	33.3	31.6	1.7
			34.9	33.5	1.4	39.1	37.2	1.9	34.4	32.9	1.5	33.9	31	2.9	33	31.4	1.6
	II year	1. measuring	35.8	34.3	1.5	38.1	36.9	1.2	31.7	30.8	0.9	31.9	29.3	2.6	38.3	36	2.3
			35.8	34.5	1.3	38.6	37.5	1.1	31.4	30.6	0.8	32.3	30	2.3	37.8	35.6	2.2
		2. measuring	55.3	54.2	1.1	42.3	40.8	1.5	31.1	29.8	1.3	28.1	26.6	1.5	43	41.9	1.1
			55.2	54.3	0.9	42.2	40.9	1.3	31.7	30	1.7	28.5	27.4	1.1	43.6	41.9	1.7
		3. measuring	35.8	33.7	2.1	38	37	1	33.6	31.7	1.9	31.9	29	2.9	35	32.7	2.3
			36.3	33.8	2.5	38.4	37.5	0.9	33	31.3	1.7	31.4	28.4	3	34.8	32.7	2.1
SUMMER	I year	1. measuring	64.8	62.3	2.5	65.3	64.1	1.2	61.7	60.2	1.5	62.1	58.9	3.2	62.7	61.8	0.9
			64.7	62.5	2.2	65.2	64.3	0.9	61.9	60.5	1.4	61	57.4	3.6	63.1	62	1.1
		2. measuring	57.5	56.3	1.2	59.3	57.5	1.8	56.2	53.8	2.4	55.2	53.6	1.6	58.9	57.2	1.7
			58.9	57.7	1.2	60.5	58.8	1.7	56.9	54.5	2.4	55	53.5	1.5	63.9	62.7	1.2
		3. measuring	59.1	58.4	0.7	67.2	63.5	3.7	61.8	59.9	1.9	62.4	59.1	3.3	62.1	60.5	1.6
			59	58.2	0.8	67.1	63.8	3.3	61.9	60.4	1.5	62.3	59	3.3	62.2	60.4	1.8
	II year	1. measuring	56.8	55.1	1.7	52.8	50.9	1.9	47.9	46.3	1.6	47.9	46.8	1.1	53.2	52	1.2
			55.3	54.2	1.1	52	50.3	1.7	47.6	46.1	1.5	48	46.3	1.7	53.9	52.8	1.1
		2. measuring	51.3	49.4	1.9	54.5	52	2.5	58.9	56.8	2.1	53.8	51	2.8	46.9	45.7	1.2
			51.8	49.8	2	55.6	53.3	2.3	58.6	56.6	2	53.7	51.4	2.3	46.4	45.3	1.1
		3. measuring	70.9	68.4	2.5	61.3	59.4	1.9	61.4	59.8	1.6	55.6	53.8	1.8	67.1	65.8	1.3
			71.5	68.2	3.3	61.1	59.5	1.6	61.9	60.4	1.5	53.9	52.1	1.8	66.1	65.1	1
AUTUMN	I year	1. measuring	58.6	55.6	3	68	65.8	2.2	61.1	59.9	1.2	56.5	54.7	1.8	63.3	61.3	2
			57.8	54.7	3.1	67.5	65.2	2.3	60.1	58.9	1.2	56.2	54.3	1.9	64.2	61.7	2.5
		2. measuring	59	57.4	1.6	57.6	55.4	2.2	56.4	54.8	1.6	61.5	58.8	2.7	61.5	59	2.5
			59.3	57.7	1.6	58.1	56.1	2	56.4	55.2	1.2	62	58.9	3.1	61.3	59	2.3
		3. measuring	62.2	61.5	0.7	58.2	56.3	1.9	55.8	54.7	1.1	61.8	59.4	2.4	62.4	60.8	1.6
			62	61.2	0.8	60.8	58.5	2.3	55.3	53.8	1.5	63.4	60.8	2.6	62.8	61.1	1.7
	II year	1. measuring	65.5	64.7	0.8	66.2	64.9	1.3	66.3	64.8	1.5	66.9	65.2	1.7	66.8	65.3	1.5
			65	64.3	0.7	66	64.6	1.4	66.5	64.7	1.8	66.8	65.4	1.4	66.9	65.2	1.7
		2. measuring	32.7	32.1	0.6	30	28.1	1.9	30.6	29.2	1.4	28.6	26.3	2.3	35.7	34.4	1.3
			32.8	32.4	0.4	29.5	27.6	1.9	30.9	29	1.9	28.3	26	2.3	35.2	34.3	0.9
		3. measuring	81.3	80.4	0.9	79.9	78.2	1.7	77.3	75.6	1.7	79.9	78.1	1.8	80.6	79.9	0.7
			81.4	80.2	1.2	79.7	78	1.7	77.4	75.5	1.9	79.7	77.6	2.1	80.1	79.3	0.8

Table 3. Average air humidity in 5 sample residential green spaces (blocks).

Season	Year	BLOCK 1			BLOCK 2			BLOCK 3			BLOCK 4			BLOCK 5		
		$H_{1\,avg}$ (%)	$H_{2\,avg}$ (%)	$H_{r\,avg}$ (%)	$H_{1\,avg}$ (%)	$H_{2\,avg}$ (%)	$H_{r\,avg}$ (%)	$H_{1\,avg}$ (%)	$H_{2\,avg}$ (%)	$H_{r\,avg}$ (%)	$H_{1\,avg}$ (%)	$H_{2\,avg}$ (%)	$H_{r\,avg}$ (%)	$H_{1\,avg}$ (%)	$H_{2\,avg}$ (%)	$H_{r\,avg}$ (%)
Spring	*I Year*	36.4	35.1	1.3	34.9	33.4	1.5	33.7	32.4	1.3	30.2	28.1	2.1	33.6	31.9	1.7
	II Year	42.4	40.8	1.6	39.6	38.4	1.2	32.1	30.7	1.4	30.7	28.5	2.2	38.8	36.8	2
	$H_{i\ avg\ tot\ season\ (i=1,2,r)}$	**39.4**	**37.95**	**1.45**	**37.25**	**35.9**	**1.35**	**32.9**	**31.55**	**1.35**	**30.45**	**28.3**	**2.15**	**36.2**	**34.35**	**1.85**
Summer	*I Year*	60.7	59.2	1.5	64.1	62	2.1	60.1	58.2	1.9	59.7	56.9	2.8	62.2	60.8	1.4
	II Year	59.6	57.5	2.1	56.2	54.2	2	56.1	54.3	1.8	52.2	50.2	2	55.6	54.5	1.1
	$H_{i\ avg\ tot\ season\ (i=1,2,r)}$	**60.15**	**58.35**	**1.8**	**60.15**	**58.1**	**2.05**	**58.1**	**56.25**	**1.85**	**55.95**	**53.55**	**2.4**	**58.9**	**57.65**	**1.25**
Autumn	*I Year*	59.8	58	1.8	61.7	59.6	2.1	57.5	56.2	1.3	60.2	57.8	2.4	62.6	60.5	2.1
	II Year	59.8	59	0.8	58.6	56.9	1.7	58.2	56.5	1.7	58.4	56.4	2	60.9	59.7	1.2
	$H_{i\ avg\ tot\ season\ (i=1,2,r)}$	**59.8**	**58.5**	**1.3**	**60.2**	**58.3**	**1.9**	**57.9**	**56.4**	**1.5**	**59.3**	**57.1**	**2.2**	**61.8**	**60.1**	**1.7**
	$H_{i\ avg\ tot\ (i=1,2,r)}$	**53.1**	**51.6**	**1.49**	**52.5**	**50.8**	**1.74**	**49.6**	**48.1**	**1.55**	**48.6**	**46.3**	**2.22**	**52.3**	**50.7**	**1.58**

Notes: $H_{1\ avg}$ – seasonal mean relative air humidity behind the green space (residential side), calculated for each season (spring, summer, autumn) across the two analyzed years (%); $H_{2\ avg}$ – seasonal mean relative air humidity in front of the green space (traffic side), calculated for each season (spring, summer, autumn) across the two analyzed years (%); $H_{r,avg\ tot}$ – seasonal mean relative humidity difference (%) $H_{r\ avg} = H_{1avg} - H_{2avg}$, representing the spatial moisture gradient generated by the green space for a given season across the two analyzed years (%); $H_{i\ avg\ tot\ season}$ (i = 1,2,r) – total seasonal mean relative air humidity values (%), behind the green space (residential side) ($H_{1\ avg\ tot\ season}$) and in front of the green space (traffic side) ($H_{2avg\ total\ season}$), calculated over two year measurements; $H_{i\ avg\ tot}$ (i = 1,2,r) – total overall mean relative air humidity behind the green space (residential side) ($H_{1avg\ tot}$) and in front of the green space (traffic side) ($H_{2avg\ tot}$), calculated across all combined seasons over the two-year period (%).

- Block 1: Over the two-year monitoring period, the mean relative humidity recorded at the sheltered position behind the green space ($H_{1\ avg\ tot}$) was 53.1 ± 14.16%, compared to 51.6±14.80 % at the exposed road-facing position ($H_{2\ avg\ tot}$), yielding a mean relative humidity gradient ($H_{r\ avg\ tot}$) of 1.49%. The confidence interval (CI) for the difference, at 95% confidence, ranges from 1.24 (lower) to 1.74 (upper). A statistically significant spatial moisture difference between the monitoring points was confirmed (t = 11.93, $p < 0.001$, η^2 = 0.802; Table 4). Recorded individual moisture differences ranged from a minimum of 0.4% to a maximum of 3.3%. The vegetative canopy structure of this block comprises tree-and-shrub combinations (53.37%) and standalone trees (46.63%), with a tree-to-shrub ratio of 61.5%: 38.5% and a marked dominance of deciduous over evergreen taxa (92.3%: 7.7%).
- Block 2: Over the two-year monitoring period, the mean relative humidity recorded at the sheltered position behind the green space ($H_{1\ avg\ tot}$) was 52.5 ± 15.68%, compared to 50.8 ± 15.40% at the exposed road-facing position ($H_{2\ avg\ tot}$), yielding a mean relative humidity gradient ($H_{r\ avg\ tot}$) of 1.74% (95% CI:1.53 – 1.96). A statistically significant spatial moisture difference between the monitoring points was confirmed (t = 16.79, $p < 0.001$, η^2 = 0.92; Table 4). Recorded individual moisture differences ranged from a minimum of 0.8% to a maximum of 3.7%. Land cover at this location is dominated by tree-and-shrub canopy (64.21%), followed by standalone trees (16.31%), lawns (6.68%), and paved surfaces (12.80%), with a tree-to-shrub ratio of 63.6%: 36.4% and an evergreen-to-deciduous ratio of 27.3%: 72.7%.
- Block 3: Mean relative humidity values reached 49.6 ± 15.80% at the sheltered position behind the greenery ($H_{1\ avg\ tot}$) and 48.1 ± 15.72% at the road-facing position ($H_{2\ avg\ tot}$), representing a mean relative humidity gradient ($H_{r\ avg\ tot}$) of 1.55% (95% CI: 1.43–1.68%). Analysis confirmed a statistically significant spatial moisture difference between the monitoring positions (t = 25.03, $p < 0.001$, η^2 = 0.95; Table 4). Individual moisture differences ranged from 0.8% to 2.4%. The cover structure includes paved areas (33.62%), lawns (22.75%), standalone

trees (21.19%), tree-and-shrub combinations (19.05%), and shrubs (3.39%), with a tree-to-shrub ratio of 53.8%: 46.2% and an evergreen to semi-evergreen to deciduous taxa ratio of 15.4%: 69.2%.

- Block 4: Mean relative humidity reached 48.6 ± 16.26% behind the green barrier ($H_{1\ avg\ tot}$) and 46.3 ± 16.18% at the road-facing position ($H_{2\ avg\ tot}$), corresponding to a mean relative humidity gradient ($H_{r\ avg\ tot}$) of 2.20% (95% CI: 1.99–2.45%). A statistically significant spatial moisture enrichment effect was confirmed behind the green infrastructure (t = 19.66, $p < 0.001$, η^2 = 0.92; Table 4). Recorded individual moisture differences ranged from a minimum of 1.1% to a maximum of 3.6%. The site is characterized by paved surfaces (33.98%), tree-and-shrub canopy (31.62%), lawns (20.20%), and standalone trees (14.20%), with equal ratios for evergreen-to-deciduous and shrub-to-tree taxa (18.2%: 81.8%).

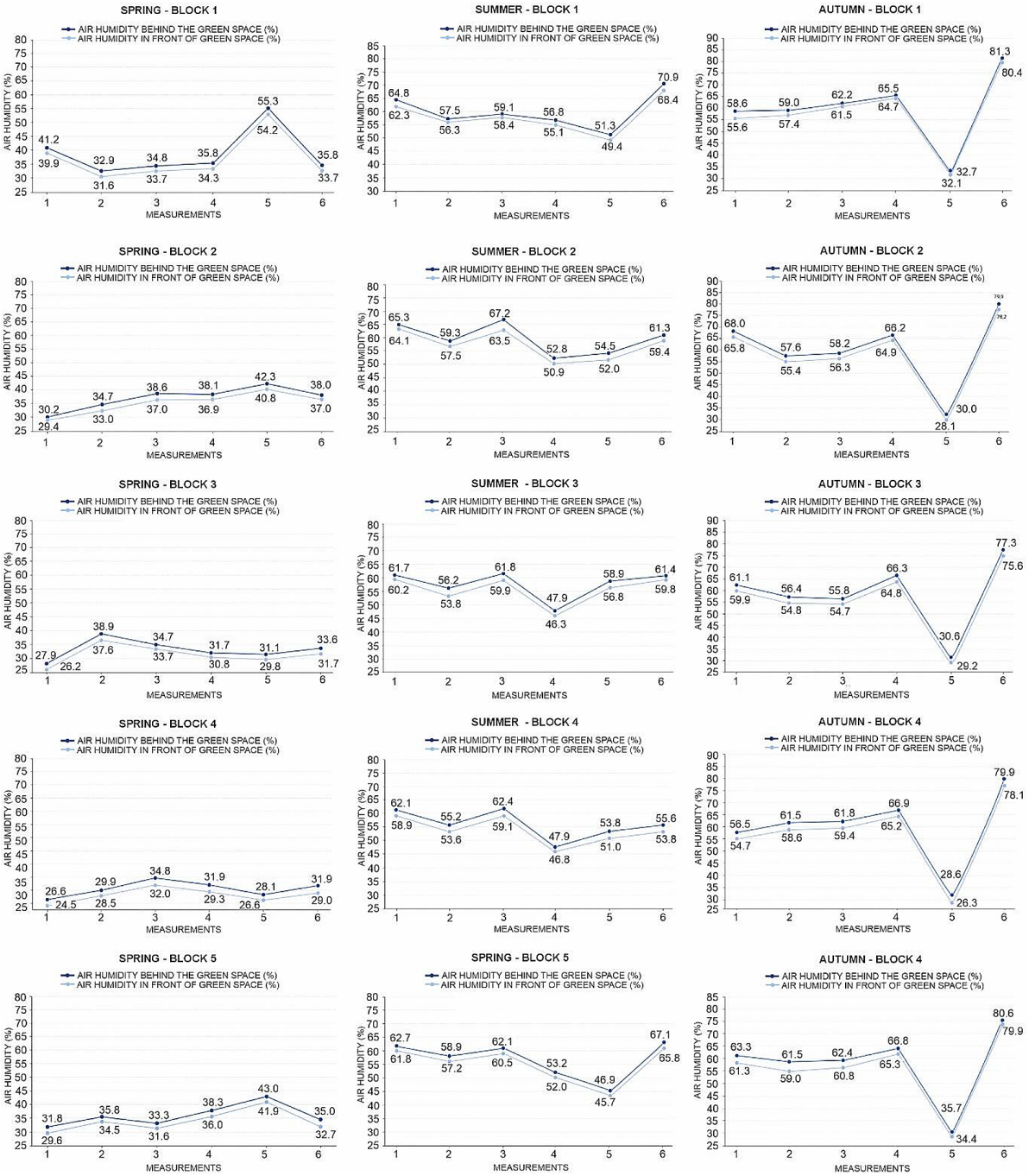


Figure 1. Air humidity values behind and in front of green space across different seasons and for 5 analysed blocks

- Block 5: The mean relative humidity recorded at the sheltered position behind the greenery ($H_{1\ avg\ tot}$) was 52.3 ± 14.86%, compared to 50.7 ± 14.70% at the road-facing position ($H_{2\ avg\ tot}$), establishing a mean relative humidity gradient ($H_{r\ avg\ tot}$) of 1.58% (95% CI: 1.41–1.75%). Statistical testing demonstrated a significant position effect on atmospheric moisture levels ($t = 18.68$, $p < 0.001$, $\eta^2 = 0.91$; Table 4). Recorded moisture differences ranged from 0.7% to 2.5%. Standalone trees constitute the primary land cover (51.55%), followed by lawns (31.10%) and paved surfaces (17.35%), with dendroflora composed exclusively of deciduous woody species (100%).

Correlations between the mean humidity values recorded at these paired monitoring positions, along with their statistical significance, are presented in Table 4.

The values of relative air humidity difference in behind and front of green space ($H_{r\ avg\ tot}$) together with the 95% confidence intervals (CI) of the $H_{r\ avg\ tot}$ for 5 analysed blocks are presented in Figure 2.

Across the total sample of 180 paired empirical measurements across the five studied locations, the overall mean atmospheric moisture gradient ($H_{ravg\ tot}$) was 1.76% (95% CI: 1.62—1.81 %) (Table 5). Relative air humidity was statistically significantly higher on the residential-facing side ($H_{1avg\ tot}$) compared to the road-facing corridor ($H_{2avg\ tot}$) ($t = 35.8$, $p < 0.001$; Table 5), yielding an overall ecohydrological effect size of $\eta^2 = 0.87$.

DISCUSSION

The present study demonstrates that residential green spaces located along major urban traffic corridors in New Belgrade act as functional ecohydrological buffers within the atmospheric boundary layer. Across all evaluated sites, the protective vegetation barriers significantly altered the microclimatic moisture regime, generating a persistent positive spatial humidity gradient on the sheltered residential side. These empirical findings align with previous observations by Chang et al. (2007), confirming that small urban green spaces (≤ 1 ha) exert a measurable modifying effect on ambient moisture dynamics.

Across the multi-year monitoring period, recorded individual spatial humidity gradients ranged from a minimum modification of 0.4% (observed during autumn in Block 1) to a maximum of 3.7% (recorded during summer in Block 2). This operational range is consistent with the ecohydrological findings of Amani-Beni et al. (2018) in the Beijing Olympic Park, where vegetative canopies induced relative air humidity increases ranging from 2.39% to 3.74% during peak summer months.

From a physical perspective, this micro-scale hydrological regulation is governed by two coupled processes: transpirational vapor injection (root-water uptake from sub-surface soil reservoirs is translocated through plant vascular systems and discharged into the lower atmosphere via foliar stomatal transpiration, directly elevating local vapor mass fraction); microclimatic canopy buffering (dense vegetative canopies attenuate local wind velocity, reducing turbulent moisture dispersion and trapping transpired water vapor. Simultaneously, canopy shading limits surface solar radiation absorption, reducing local sensible heat flux and saturation vapor pressure, thereby elevating measured relative air humidity).

The near-perfect linear correlation coefficients recorded across all sites ($r \geq 0.999$, $p < 0.001$) reflect the primary control of macro-meteorological forcing over baseline atmospheric conditions. However, the exceptionally high t -statistic values ($11.93 \leq t \leq 25.03$, $p < 0.001$) and large effect sizes ($\eta^2 \geq 0.803$) confirm that despite shared background weather patterns, the presence of green infrastructure imposes a statistically significant, systematic upward shift in the local moisture balance.

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Spatial analysis indicates that the magnitude of local atmospheric moisture enrichment ($H_{r\ avg}$)

Table 4. The impact of residential green space on air humidity

BLOCK 1			$H_{iavgtot\ (i=1,2)}$	N	S	S_S	Correlation		Sig.
Air humidity behind the green space (H_1)			53.1	36	14.16	2.36	0.999		0.000
Air humidity in front of green space (H_2)			51.6	36	14.08	2.35			
Air humidity in behind and front of green space	$H_{ravg\ tot}$	S	S_s	95% Confidence Interval of the Difference			t	df	Sig.
				Lower		Upper			
	1.49	0.75	0.12	1.24		1.74	11.93	35	0.000
BLOCK 2			$H_{iavgtot\ (i=1,2)}$	N	S	S_S	Correlation		Sig.
Air humidity behind the green space (H_1)			52.5	36	15.68	2.61	0.999		0.000
Air humidity in front of green space (H_2)			50.8	36	15.40	2.57			
Relative air humidity difference in behind and front of green space	$H_{ravg\ tot}$	S	S_s	95% Confidence Interval of the Difference			t	df	Sig.
				Lower		Upper			
	1.74	0.62	0.10	1.53		1.96	16.79	35	0.000
BLOCK 3			$H_{iavgtot\ (i=1,2)}$	N	S	S_S	Correlation		Sig.
Air humidity behind the green space (H_1)			49.6	36	15.80	2.63	1.000		0.000
Air humidity in front of green space (H_2)			48.1	36	15.72	2.62			
Relative air humidity difference in behind and front of green space	$H_{ravg\ tot}$	S	S_s	95% Confidence Interval of the Difference			t	df	Sig.
				Lower		Upper			
	1.55	0.37	0.06	1.43		1.68	25.03	35	0.000
BLOCK 4			$H_{iavgtot\ (i=1,2)}$	N	S	S_S	Correlation		Sig.
Air humidity behind the green space (H_1)			48.6	36	16.26	2.70	0.999		0.000
Air humidity in front of green space (H_2)			46.3	36	16.18	2.71			
Relative air humidity difference in behind and front of green space	$H_{ravg\ tot}$	S	S_s	95% Confidence Interval of the Difference			t	df	Sig.
				Lower		Upper			
	2.22	0.68	0.11	1.99		2.45	19.66	35	0.000
BLOCK 5			$H_{iavgtot\ (i=1,2)}$	N	S	S_S	Correlation		Sig.
Air humidity behind the green space (H_1)			52.3	36	14.86	2.45	0.999		0.000
Air humidity in front of green space (H_2)			50.7	36	14.70	2.48			
Relative air humidity difference in behind and front of green space	$H_{ravg\ tot}$	S	S_s	95% Confidence Interval of the Difference			t	df	Sig.
				Lower		Upper			
	1.58	0.51	0.08	1.41		1.75	18.68	35	0.000

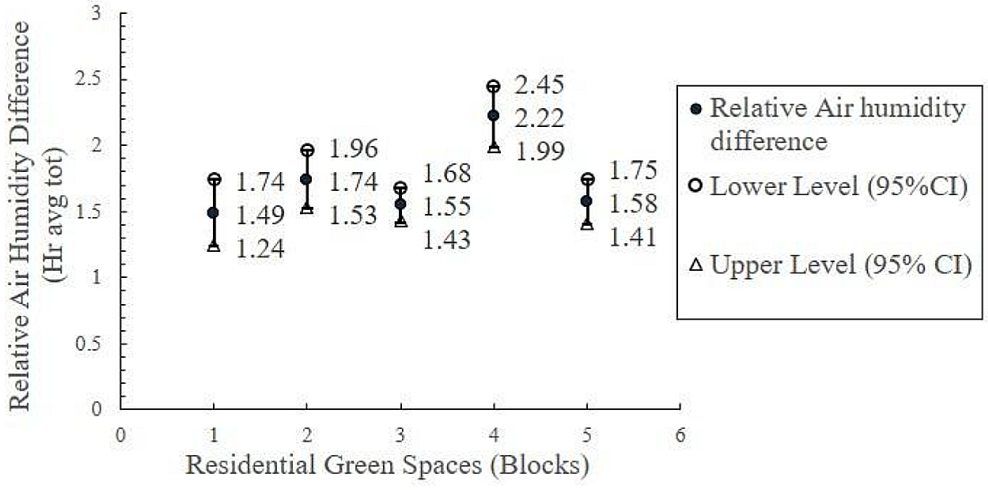

Figure 2. Relative air humidity difference in behind and front of green space ($H_{r\ avg\ tot}$) and the 95% confidence intervals (CI) of the *Hr avg tot* for 5 analysed blocks

Table 5. Impact of residential green space on air humidity - overall statistical indicators for blocks (1, 2, 3, 4 and 5).

Parameter			$H_{i\ avgtot}$ (i=1,2)	N	S	S_S	Correlation		Sig.
Air humidity behind the green space (H_1)			51.8	36	15.29	1.14	0.999		0.000
Air humidity in front of green space (H_2)			50.0	36	15.25	1.14			
Air humidity in behind and front of green spaces	$H_{r\ avg\ tot}$	S	S_s	95% Confidence Interval of the Difference		t	df	Sig.	
				Lower	Upper				
	1.76	0.65	0.05	1.62	1.81	35.8	179	0.000	

does not scale linearly with total green space area. Sites measuring 0.7 ha yielded mean humidity increases of 1.58% (Block 5) and 1.74% (Block 2), whereas larger spatial units measuring 1.2 ha and 1.4 ha exhibited lower mean increases of 1.49% (Block 1) and 1.55% (Block 3). Notably, the highest overall mean moisture enhancement ($H_{r\ avg}$=2.22%) was recorded in Block 4, which covers an intermediate area of 1.2 ha.

These empirical trends conform to the microclimatic principles established by Chang et al. (2007), who observed that green spaces smaller than 3 ha display substantial internal microclimatic variability, whereas linear scaling effects emerge predominantly in contiguous spaces exceeding 3 ha. In smaller urban blocks, canopy structure and vertical biomass density supersede spatial area as the primary drivers of ecohydrological moisture regulation.

The crucial role of canopy structure is evident when comparing sites with high vertical complexity. The maximum moisture gradients were recorded in Block 4 ($H_{r\ avg}$=2.22%) and Block 2 ($H_{r\ avg}$=1.74%). Although differing in spatial extent (1.2 ha vs. 0.7 ha), both locations feature a high proportion of multi-layered, combined tree-and-shrub canopy cover (31.62% trees + 31.62% combinations in Block 4; 64.21% combinations in Block 2). Furthermore, when comparing two sites of identical spatial area (0.7 ha), Block 2 generated a higher moisture enhancement (1.74%) than Block 5 (1.58%). This difference is directly attributable to the 56.2% greater woody canopy coverage in Block 2.

These results reinforce the ecohydrological principle that multi-layered canopy structures maximize the effective Leaf Area Index (LAI) per unit ground area. A higher LAI increases total stomatal surface area available for transpiration while enhancing aerodynamic drag, which slows wind movement and retards the escape of transpirational water vapor into the turbulent urban boundary layer. This closely mirrors the observations of Amani-Beni et al. (2018), who recorded peak humidity levels beneath dense, high-canopy stands equipped with well-developed shrub understories.

Morphological, anatomical, and dendrological traits of constituent woody taxa further regulate the rate of evapotranspirational moisture flux into the urban microclimate.

Sites exhibiting superior humidity modification, such as Block 2 ($H_{r\ avg}$= 1.74%) and Block 5 ($H_{r\ avg}$= 1.58%), are characterized by high proportions of deciduous taxa and prominent representation of species featuring specific functional foliar traits: dark foliage (*Acer pseudoplatanus* 'Atropurpureum', *Prunus cerasifera* 'Atropurpurea', *Syringa vulgaris* L., *Berberis vulgaris* L.); broad leaf blades (*Tilia tomentosa* Moench., *Acer pseudoplatanus* L.); coriaceous (leathery) leaf surfaces (*Prunus laurocerasus* L., *Ulmus pumila* L.).

These findings fully conform to the classical biometeorological framework of Oke (1989). Broad, dark-colored foliage exhibits lower shortwave albedo and higher solar radiation absorption. This absorbed energy drives the latent heat flux (λE) by accelerating stomatal transpiration rather than sensible heating, provided root-zone moisture is non-limiting. Concurrently, broad and coriaceous leaf structures maintain robust boundary layer resistance and stomatal control under summer vapor pressure deficits, sustaining active transpiration during peak thermal conditions.

Conversely, lower mean moisture gradients were observed in Block 1 ($H_{r\ avg}$= 1.49%) and Block 3 ($H_{r\ avg}$= 1.55%), despite their larger spatial areas (1.2 ha and 1.4 ha). The flora at these sites is dominated by taxa with light-colored, thin leaf blades (*Betula pendula* Roth, *Celtis occidentalis* L., *Fraxinus lanceolata* Borkh., *Forsythia* × *intermedia* Zabel, *Koelreuteria paniculata* Laxm., *Forsythia suspensa* (Thunb.) Vahl, *Spiraea* × *vanhouttei* (Briot) Carrière, *Hibiscus syriacus* L., *Philadelphus coronarius* L.), alongside

high shrub proportions (38.5% and 46.2%) and over 65% deciduous species. Foliar canopies dominated by lighter, thinner leaves absorb less net radiation and generally possess lower single-leaf transpiration capacities, yielding a more subdued localized humidification effect.

Finally, the lowest overall moisture modification ($H_{r\ avg}$ = 1.49%) occurred in Block 1 (1.2 ha). Although this site possesses 100% vegetative cover (trees and shrubs), it is directly adjacent to an international highway corridor (E-75), a significantly wider, more heavily trafficked arterial road than those bordering the other blocks.

Extensive asphalt surfaces and intense vehicular traffic act as strong anthropogenic heat sources that generate localized dry microclimates, thermal updrafts, and strong advective wind shear. These advective processes accelerate the mechanical dispersion of transpirational water vapor away from the vegetative canopy, reducing the localized humidity buildup behind the green belt.

This boundary-layer interaction highlights a crucial ecohydrological planning requirement: the spatial width, canopy density, and vertical structure of protective green belts must be scaled proportionally to the thermal and aerodynamic intensity of adjacent traffic corridors. To mitigate the dry microclimatic footprint of multi-lane, heavily congested roadways, urban green belts must be designed not merely as continuous ground cover, but as multi-layered, high-LAI ecohydrological barriers capable of sustaining high latent heat fluxes while resisting mechanical vapor displacement.

CONCLUSIONS

This study provides empirical evidence of the vital ecohydrological role of residential green spaces along major traffic corridors in regulating air humidity within the urban boundary layer of New Belgrade. The findings from multi-year monitoring confirm the initial research hypothesis: protective green belts along high-density traffic corridors exert a statistically significant, continuous, and positive impact on the microclimatic moisture regime, establishing a stable spatial humidity gradient (H_r) with higher relative air humidity levels on the sheltered residential side (H_1) compared to the exposed traffic side (H_2).

The conducted analysis yields several key scientific and practical insights, demonstrating that despite the dominant influence of meteorological conditions, residential green spaces act as effective ecohydrological buffers. The overall mean atmospheric moisture enrichment across all study sites was 1.72%, with individual spatial gradients ranging from autumn to summer, which aligns with international research in similar urban ecosystems.

Furthermore, the magnitude of atmospheric moisture enrichment does not scale linearly with total green space surface area. In smaller urban spatial units (≤ 1.4 ha), vertical complexity and biomass density surpass land area as the main drivers. The highest humidity gradients were recorded at sites with a high proportion of multi-layered tree-and-shrub combinations (Block 4 with $H_{r\ avg}$ = 2.22% and Block 2 with $H_{r\ avg}$ = 1.74%), confirming that multi-layered structures maximize the Leaf Area Index (*LAI*) and retard the turbulent dispersion of transpired water vapor.

Additionally, dendrological composition and functional leaf properties play a crucial role in regulating atmospheric moisture. Taxa featuring broad, darker, and coriaceous (leathery) leaves (*Acer pseudoplatanus* L., *Tilia tomentosa* Moench, *Prunus laurocerasus* L., *Prunus cerasifera* Ehrh. 'Atropurpurea') exhibit more pronounced humidity regulation. Due to lower shortwave albedo and higher solar radiation absorption, these species efficiently convert absorbed radiative energy into latent heat flux (Q_e) via intensive stomatal transpiration, thereby maintaining a robust atmospheric moisture regime even during peak summer thermal conditions.

Finally, the intensity of the adjacent traffic corridor directly affects the micro-hydrological balance. Extremely wide and heavily trafficked arteries (such as the E-75 highway corridor bordering Block 1) generate strong thermal updrafts and advective wind shear, which accelerate the mechanical dispersion of water vapor and diminish the localized humidification effect despite vegetative cover.

The empirical findings of this research provide practical guidelines for urban planners, landscape and ecological engineers and municipal green infrastructure managers. It can be concluded that the width, canopy density, and *LAI* of protective green belts should be scaled proportionally to the thermal and vehicular load of adjacent traffic corridors to effectively counter localized dry microclimates. When designing and redesigning residential greenery, priority must

be given to multi-layered plantings that combine high trees with a dense shrub understory, avoiding monocultures and simplified turfgrass lawns. In addition, dendrological selection should favor deciduous species with broad leaf blades and high transpirational capacity that demonstrate resistance to urban stress and summer vapor pressure deficits. In conclusion, the systematic planning and long-term management of residential greenery represent an indispensable ecohydrological strategy for mitigating urban heat island effects, improving bioclimatic comfort, and enhancing long-term urban climate resilience.

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