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RESEARCH ARTICLE

Planting for healthy air: Urban biodiversity enhances natural chemical environments

Aurora Ruggeri[1] | Fethi Ben Fraj[2] | Gaetan Glauser[3] | Gregory Röder[2] | Ola Söderström[1] | Sergio Rasmann[2]

[1]Institute of Geography, University of Neuchâtel, Neuchâtel, Switzerland

[2]Institute of Biology, University of Neuchâtel, Neuchâtel, Switzerland

[3]Neuchâtel Platform of Analytical Chemistry, Faculty of Science, University of Neuchâtel, Neuchâtel, Switzerland

Correspondence
Aurora Ruggeri, Institute of Geography, University of Neuchâtel, Espace Tilo-Frey 1, 2000 Neuchâtel, Switzerland.
Email: aurora.ruggeri@unine.ch

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Societal Impact Statement

Cities urgently need nature to improve public health, support biodiversity, and increase resilience to climate change. Yet not all green spaces offer the same benefits. In this study, we show that more diverse urban plantings create richer "chemical environments"; subtle, naturally scented atmospheres formed by plant emissions that can influence how people feel and recover from stress. By revealing this hidden dimension of human–plant interaction, our work suggests that planting a greater variety of species in parks and streets could enhance everyday well-being while supporting wildlife and climate goals. These insights can guide city planners, public health professionals, and community groups in designing greener, healthier cities for all.

Summary

- Urban green spaces are known to support human well-being, yet we still lack a clear understanding of which plant characteristics and green spaces configurations create the most psychologically and physiologically beneficial urban environments. Stress reduction and restorative properties of green spaces are often emphasized, but the mechanisms underlying those benefits are still unclear. But plants also shape city air through the release of natural volatile compounds that can influence human physiology and health. We aimed to determine whether more botanically diverse parks also create richer chemical environments, revealing a hidden dimension of human–plant connection in cities.
- We measured plant species richness and vertical vegetation structure across public parks in Lausanne, Switzerland, and collected airborne volatile organic compounds (VOCs) directly in each park. We combined vegetation surveys, air sampling, and species-level phytochemistry data to test whether plant diversity predicts VOC richness and chemical richness in real and simulated plant communities.
- Plant communities differed strongly among parks and across vegetation layers, and parks with higher plant diversity also exhibited higher chemical diversity in the air. Phylogenetic mapping revealed lineage-level variation in chemical

potential, and simulated plant assemblages confirmed a consistent positive relationship between botanical richness and chemical richness.

- Our findings show that biodiversity shapes an overlooked chemical dimension of urban nature, suggesting that diverse plantings may enhance the atmospheric qualities that help people reduce stress, recover, and connect with natural environments. Considering plant chemical diversity in urban greening strategies could enhance stress reduction and increase biodiversity, fostering healthier and more resilient cities.

KEYWORDS

airborne chemistry, biodiversity, human–plant interactions, plant volatiles, sensory ecology, urban ecology, urban greening, volatile organic compounds

1 | INTRODUCTION

Urban green spaces are essential to the physical and psychological well-being of city dwellers. A growing body of research demonstrates that exposure to nature is associated with improved general health, including reduced chronic disease burden and enhanced social functioning (Browning et al., 2022; McCay et al., 2017). Living near parks and tree-lined streets correlates with lower risks of depression and anxiety (Bakolis et al., 2018) and city residents who interact with green spaces report reduced stress, improved attention, and greater social cohesion (Roe & McCay, 2021; World Health Organization, 2021). Green infrastructure also supports physical activity through walkable and shaded environments (McDonald & Beatley, 2020) and contributes to reduced cardiovascular and metabolic disease risks (Kua & Sia, 2017; Lee & Maheswaran, 2011). These benefits extend beyond individual health to the broader urban environment, moderating heat during the summer months, improving air quality, buffering noise, and supporting biodiversity (World Health Organization, 2021).

Despite this growing evidence base, most studies implicitly treat urban green space as a homogeneous category or a conceptual simplification that obscures the diversity of ecological forms urban nature can take. Indeed, only half of studies across the life, physical, and social sciences explicitly define "green space" (Taylor & Hochuli, 2017). Without considering variation in plant species composition, structural complexity, or size, it remains difficult to determine which types of urban nature most effectively promote well-being. Such nuance is essential for understanding how different ecological, spatial, and botanical configurations mediate nature–health relationships and for designing cities that provide these benefits equitably.

Three influential frameworks, the Biophilia Hypothesis (Kellert & Wilson, 1995), Stress Reduction Theory (Ulrich et al., 1991), and Attention Restoration Theory (Kaplan, 2001), offer compelling explanations for nature's positive effects, proposing that humans have evolved to respond emotionally, physiologically, and cognitively to natural environments. Natural settings may reduce stress by eliciting feelings of safety and fascination (Ulrich et al., 1991; White & Shah, 2019), or support attentional recovery by engaging effortless attention (Kaplan, 2001). Nevertheless, while these theories highlight humans' deep emotional and perceptual ties to plants, they focus largely on visual and spatial dimensions of nature, such as trees, views, and patterns of light and green.

Yet, plants shape human experience not only through what we see, but also through what we breathe. Indeed, a fraction of the biochemical composition that makes up the vegetation phenotype is composed of complex blends of volatile organic compounds (VOCs), including terpenes, phenylpropanoids, or fatty acid derivatives (Pichersky & Raguso, 2018). A growing body of literature suggests that terpenoids, in particular, may contribute to stress relief, immune modulation, and mood enhancement (Masyita, Sari, et al., 2022; Willis, 2024), with forest studies showing measurable monoterpenes in air humans inhale (Bach et al., 2020; Zorić et al., 2022). Such findings connect sensory perception, such as the familiar "scent of the forest" (Cho et al., 2017), to plausible biochemical mechanisms underlying nature's stress relief effects. While widely studied in forest medicine, the potential role of plant-derived VOCs in urban well-being remains understudied, even though urban parks often contain richly scented plant species and moments where volatiles are perceptible to park visitors.

Plant species differ dramatically in the types and amounts of metabolites they produce (Defossez et al., 2021; Futuyma & Agrawal, 2009; Pichersky et al., 2006; Walker et al., 2023), suggesting that differences in botanical composition could drive meaningful variation in the "chemical landscapes" (Hunter, 2016) of cities. Yet, urban green planning rarely considers chemical diversity as an ecological or human-relevant attribute (Casanelles-Abella et al., 2025). When chemical aspects are taken into account, they typically relate to practical concerns such as allergenicity or the toxicity of certain species, which are therefore often avoided or restricted in urban green spaces (Stevanovic et al., 2025). Therefore, considering the role of VOCs as potential determinants of human health represents an untapped opportunity: If different plant communities generate distinct chemical environments, then biodiversity may influence not only the aesthetics

and structure of urban green spaces but also their potential to support human health.

Here, we explore whether urban plant diversity predicts both volatile and nonvolatile chemical diversity in public parks in the city of Lausanne, Switzerland. We mapped vegetation across vertical strata (ground, shrub, and tree layers), characterized airborne VOCs in situ, and quantified leaf phytochemical richness across dominant plant species. We then examined the relationship between botanical diversity and chemical richness and asked whether more species-rich spaces create more chemically complex human sensory environments. By integrating plant ecology, metabolomics, and urban human nature research, we reveal that the benefits of biodiverse urban nature extend beyond form and color, while reaching into the invisible chemical dimension of human–plant interactions in cities.

2 | MATERIAL AND METHODS

2.1 | Study area and site selection

Fieldwork was conducted in 12 public parks within Lausanne, Switzerland (46.5191° N, 6.6333° E). Sites were selected within an ongoing interdisciplinary project on urban environments and mental health, focusing on green spaces identified as particularly appreciated by participants with a diagnosis of psychosis (this study received approval from the Cantonal Research Ethics Committee: CER-VD—reference no. 2022-02257). From this broader set, we selected parks to represent the range of urban green typologies present in Lausanne, capturing variation in vegetation structure, management intensity, and surrounding land cover. While no strict quantitative thresholds (e.g., minimum park size or fixed imperviousness gradients) were imposed a priori, site selection was guided by land-use/land-cover (LULC) data and field observations to ensure coverage of contrasting park configurations (Figure S1). In each park, three vertical strata were sampled to capture potential variation in chemical and biological composition: (i) ground layer (0 m), (ii) shrub layer (≈ 1 m), and (iii) lower tree canopy (≈2 m), corresponding to a standardized height within the human breathing zone and the lower portion of the tree layer, rather than the full canopy height, to ensure comparability across parks. One representative site per stratum was selected using a combination of random placement within suitable vegetation areas and consideration of typical visitor use, to capture conditions relevant to human exposure while maintaining comparability across parks, resulting in 36 sampling locations (12 parks × 3 heights, Appendix S1 for each location aerial map representation).

2.2 | LULC mapping

LULC composition within each park was quantified from the ESA WorldCover 10 m v2.0 (2021) dataset (Zanaga et al., 2022) via Google Earth Engine. Park boundaries were delineated in QGIS 3.4 using municipal GIS layers. LULC characterization was restricted to park boundaries without the inclusion of an external buffer, to focus on within-park vegetation structure and maintain comparability across sites. Zonal-statistics summaries provided proportional cover of tree, grassland, cropland, built-up, bare/sparse vegetation, and water classes; manual corrections were made using submeter satellite imagery to refine heterogeneous or small areas (Figure S2).

2.3 | Vegetation survey

Around each air-sampling device (see below), circular plots of increasing radius were delineated to match vegetation strata (3 m for ground, 5 m for shrub, and 10 m for tree layer). All vascular plant species present were identified in situ or from voucher material (Appendix S2). Species abundance was estimated visually using the Braun–Blanquet cover-abundance scale, with classes r (solitary or few individuals, negligible cover), + (<1% cover), 1 (<5% cover or few individuals with 1%–5%), 2 (5%–25%), 3 (25%–50%), 4 (50%–75%), and 5 (75%–100%) and subsequently converted to relative cover values for analysis (Ivanova, 2024). Furthermore, for each stratum, the five most abundant species (i.e., Classes 4 and 5) were sampled (leaves or needles) for chemical analyses, with multiple individuals per species when available. In total, 171 plant samples were collected across all parks and strata, representing 107 species. Replication occurred when species were sufficiently abundant within or across strata, such that the same species could be sampled multiple times within a park if present in more than one vegetation layer. Rarer species were not systematically included, as sampling focused on dominant vegetation component (Appendix S3).

2.4 | Air sampling of VOCs

Ambient air was sampled for VOCs using portable pocket pumps (AirCheck Touch, SKC Inc. Eighty Four, PA, USA) connected to activated-carbon adsorption tubes (ORBO™ 32 Small Activated Coconut Charcoal [20/40], 100/50 mg, Merck KGaA, Darmstadt, Germany). Pumps were operated at 200 mL/min for 210 min per site, corresponding to a sampled volume of approximately 42 L of air. Samplers were positioned at target heights (0, ∼1, and ∼2 m) within each vegetation stratum, adjacent to representative vegetation, and operated under ambient conditions (natural sunlight) during dry, sunny weather. All sites were sampled under comparable conditions and away from immediate anthropogenic sources. Sampling was carried out during a single campaign in July (2–24)/August 13, 2024, within a standardized daytime window (late morning to early afternoon) to minimize temporal variability in VOC emissions. Field and laboratory blanks were included to account for background contamination. Filters were capped immediately after collection, transported on ice, and stored at −20°C until gas chromatography–mass spectrometry (GC–MS) analysis (see below).

2.5 | VOC extraction and GC–MS profiling

Adsorbent filters were eluted with high-purity solvent (HPLC grade dichloromethane; CAS# 75-09-2) containing 19.9-µg/µL naphthalene (CAS# 91-20-3, from Merck) as internal standard. Extracts were stored at −20°C until analysis by gas chromatography–mass spectrometry (GC–MS; Agilent 7890B GC coupled to 5977B MSD) following Tholl et al. (2006). Compound peaks were integrated in MZmine v2.53 (Pluskal et al., 2010). VOC features were defined as chromatographic peaks exceeding a signal-to-noise threshold (S/N > 3), aligned across samples based on retention time and mass spectral similarity. Compound annotation was performed where possible using spectral libraries, but richness estimates were based on aligned features.

2.6 | Nonvolatile metabolite extraction and LC–MS profiling

Leaf samples were freeze-dried, milled to a fine powder, and extracted (20-mg dry weight) in 1 mL of water–methanol–formic acid (30:69.9:0.1). Extracts were centrifuged (14,000 g, 5 min), and supernatants were collected, recentrifuged, and transferred to vials for LC–MS analysis. Specifically, aqueous methanolic leaf extracts of each plant species sample were analyzed by ultrahigh performance liquid chromatography–quadrupole time-of-flight mass spectrometry (UHPLC-QTOFMS) using an Acquity UPLC™ I-Class coupled to a SYNAPT XS (Waters, Milford, USA) (Defossez et al., 2023). The system was controlled by MassLynx v.4.2. An Acquity UPLC™ HSS T3 column (100 × 2.1 mm, 1.8 µm) maintained at 25°C was used at a flow rate of 0.5 mL/min. Mobile phases consisted of H2O + 0.05% formic acid (solvent A) and acetonitrile +0.05% formic acid (solvent B). A linear gradient from 0 to 100% B in 10.0 min was applied. The injection volume was 0.5 µL. MS detection was performed in negative electrospray ionization and using data-dependent acquisition (DDA). The resolution was set to 22,000 (at m/z 554). Data were acquired in continuum mode. The capillary voltage was set to −1.0 kV, the cone voltage to −25 V, the source temperature to 140°C, the desolvation temperature to 500°C, the desolvation gas flow to 1000 L/h, the cone gas flow to 150 L/h, the nebulizer gas flow to 6.5 bars, and the collision gas (Ar) flow to 2.0 L/min. DDA settings were as follows: MS1 mass range and scan time 50–1200 Da and 0.1 s, respectively, top 7 MS/MS (0.05 s scan time each), intensity threshold 15,000 counts per s, MS/MS selection window 4 Da, peak deisotoping activated, dynamic exclusion of 1.5 s after acquisition. An exclusion list of the 150 most intense background ions was generated from a blank sample run just before the plant samples. For MS/MS acquisition, a ramped collision energy of 5–40 V (at m/z 50) and 20–70 V (at m/z 1200) was set. Quality control samples were prepared by pooling aliquots of all samples and run four times before the batch and about every 30 samples during the batch.

Feature detection in MzMine V.3 (Schmid et al., 2023) was performed using noise levels for MS1 and MS2 of 1500 and 40, respectively. The parameters for ADAP chromatogram builder were minimum group size in number of scans 5, group intensity threshold 2000, minimum height intensity 2000, m/z tolerance 0.015 Da or 15 ppm. The chromatogram deconvolution algorithm used was wavelets (ADAP), and parameters were: Threshold 10, minimum feature height 1500, coefficient/area Threshold 50, peak duration range 0.01–0.5 min, RT wavelet range 0.00–0.06, m/z center calculation median, m/z and RT range for MS2 scan pairing 0.1 and 0.12. The isotope peak grouper parameters were m/z tolerance 0.015 Da or 15 ppm, retention time tolerance 0.07, maximum number of charges 2, most intense isotope. The joint aligner parameters were m/z tolerance 0.015 Da or 15 ppm, retention time tolerance 0.1, weight for m/z 50, weight for RT 50. Only features with a minimum of 2 isotopes and MS2 spectra were retained by filtration. No gap-filling was applied.

2.7 | Data processing and statistical analyses

All analyses were conducted in R (Team, 2018), with the *vegan* (Oksanen et al., 2013), *rotl* (Michonneau et al., 2016), *stringdist* (van der Loo, 2014), *ape* (Paradis et al., 2004), and *tidyverse* (Wickham et al., 2019) packages; graphics were produced with *ggplot2* (Wickham, 2011), *ggtree* (Yu et al., 2017), and *ggpubr* (Kassambara, 2025).

2.8 | Vegetation

We assembled a site × species presence–absence matrix for the 36 plots (12 parks × 3 strata: herb, shrub, and tree). Community dissimilarity among plots was computed with the Jaccard index on binary data (*vegan::vegdist*, binary = TRUE), and ordinated via nonmetric multidimensional scaling with two axes (*vegan::metaMDS*, $k = 2$, trymax = 100). Differences in floristic composition among vegetation layers were tested with PERMANOVA (*vegan::adonis2*) using 199 permutations and restricting permutations within-park identity to account for spatial grouping. Homogeneity of multivariate dispersion among vegetation layers was assessed using the *vegan::betadisper* function prior to PERMANOVA. Alpha diversity per plot was quantified as species richness (*vegan::specnumber*). To derive park-level diversity, we pooled plot matrices by park (rowsum across the three strata) and computed total species richness on the pooled matrices. We summarized park-level richness as mean ± standard error.

2.9 | VOCs and vegetation

GC–MS peak areas were matched to sample metadata, and intensities were normalized to the internal standard (IS) by dividing each compound's area by the IS area. Community structure of VOC profiles was ordinated with nonmetric multidimensional scaling (*vegan::metaMDS*, Bray–Curtis distance, two dimensions). Differences in VOC composition among vegetation layers (herb, shrub, and tree) were

tested with PERMANOVA (*vegan::adonis2*, 199 permutations) with permutations restricted within park to control for spatial grouping. To relate chemistry to plants, we quantified VOC alpha diversity as compound richness per sampling unit (*vegan::specnumber*) and paired it with plant richness computed for the same units. The association between plant richness and VOC richness was evaluated with an ordinary least squares model including park as a blocking factor, with inference based on ANOVA of the fitted model. Visualizations comprised an NMDS biplot with 95% confidence ellipses by vegetation layer and a scatterplot of plant versus VOC richness with an ordinary least square smoothing.

2.10 | Simulations, rarefaction, and phylogenetic mapping

To embed species in a phylogenetic framework, we compiled all focal taxa, standardized scientific names (accent removal, case normalization, and punctuation removal) and resolved names against the Open Tree of Life (*rotl::tnrs_match_names*). We obtained the induced subtree containing all matched taxa (*rotl::tol_induced_subtree*) by stripping Open Tree Taxonomy identifiers. When necessary, unmatched names were reconciled using fuzzy matching (*stringdist::amatch*). Chemical richness was joined to tree tips, and the phylogeny was visualized in circular layout with metabolite richness mapped to tip color and point size (*ggtree*). To test whether richer plant assemblages generate richer chemical environments (in terms of the entire specialized metabolome of plants), we simulated virtual communities by sampling species from the empirically observed pool while constraining draws to the measured vertical strata proportions (herb 0.358, shrub 0.328, and tree 0.313). For each virtual community size, for each simulated community, we recorded (i) the number of species drawn and (ii) total chemical richness, defined as the number of unique metabolites present across constituent species (logical union across rows). Simulated communities were generated by randomly sampling species from the observed pool without replacement. Simulations were run for community sizes from 3 to 80 species, with 100 replicates per size. Phylogenetic mapping and virtual community simulations were based exclusively on the LC–MS dataset; GC–MS VOC data were analyzed separately and were not combined with LC–MS features in richness simulations.

3 | RESULTS

3.1 | Urban vegetation exhibits strong compositional and structural heterogeneity

Across the 12 Lausanne parks, plant communities varied substantially in both species ($n = 177$ unique species, Appendix S2) composition and vertical structure (Figure 1). The NMDS ordination revealed clear separation among vegetation layers across all parks (Figure 1A; NMDS stress = 0.08; PERMANOVA $R^2 = 0.20$, $F_{2,35} = 4.24$, $p = 0.005$). Homogeneity of dispersion differed among vegetation layers (betadisper, $p = 0.025$), indicating that both compositional turnover and differences in within-layer heterogeneity contribute to the observed separation (Figure 1A). Mean plot-level (α-diversity) ranged from three plant species in Parc Eracom up to 28 species in the middle layer of Parc de Milan (Figure 1B; Table S1). Averaged across plots, mean species richness per park was 9.42 ±0.84 s.e.

3.2 | Parks differ in their chemical atmosphere, and plant richness predicts VOC richness

Based on our sampling and analytical method, we retained 39 unique ambient VOCs (Appendix S4), whose profiles also differed among vegetation layers (Figure 2A; NMDS stress = 0.144; PERMANOVA $R^2 = 0.118$, $F_{2,32} = 2.002$, $p = 0.005$). While VOC composition varied among parks, ordination patterns showed partial overlap, indicating that differences are not absolute. However, PERMANOVA results support significant compositional variation across sites, suggesting that parks differ in their chemical environments despite shared components. Across parks, VOC richness increased with plant diversity (Figure 2B; slope = 0.60, $R^2 = 0.15$, $F = 6.14$, $p = 0.020$). These results support the hypothesis that botanical diversity generates diversity in terms of molecular composition of urban air experienced by park users.

3.3 | Virtual community simulations and phylogeny confirm biodiversity–chemistry coupling

The LC–MS pipeline yielded a total of 8731 unique molecular features (across all species sampled) (Appendix S5), with the highest chemical diversity observed in *Taxus baccata* (1638 unique molecular features), and the lowest in *Arrhenatherum elatius* (373) (Figure S3). Simulated communities drawn from the observed species pool showed a strong, saturating increase in chemical richness with plant richness (Figure 3A; GAM model; $t = 1241$, $p < 0.001$, with edf = 8.64, $F = 15{,}218$, $p < 0.001$). The species-accumulation plot further indicated that chemical feature discovery increases steeply with added species and, with the sampled species pool, reached an asymptote at around 80 species (Figure 3A). Mapping LC–MS chemical richness onto a multispecies phylogeny (Open Tree) revealed clade-level differences in metabolite diversity (Figure S3), suggesting evolutionary structuring of chemical capabilities relevant for urban planning and ecosystem service delivery.

4 | DISCUSSION

By using empirical and simulated results we show that diverse vegetation reliably supports a richer phytochemical environment, providing mechanistic evidence that biodiversity underpins chemical pathways linking nature and human well-being in cities.

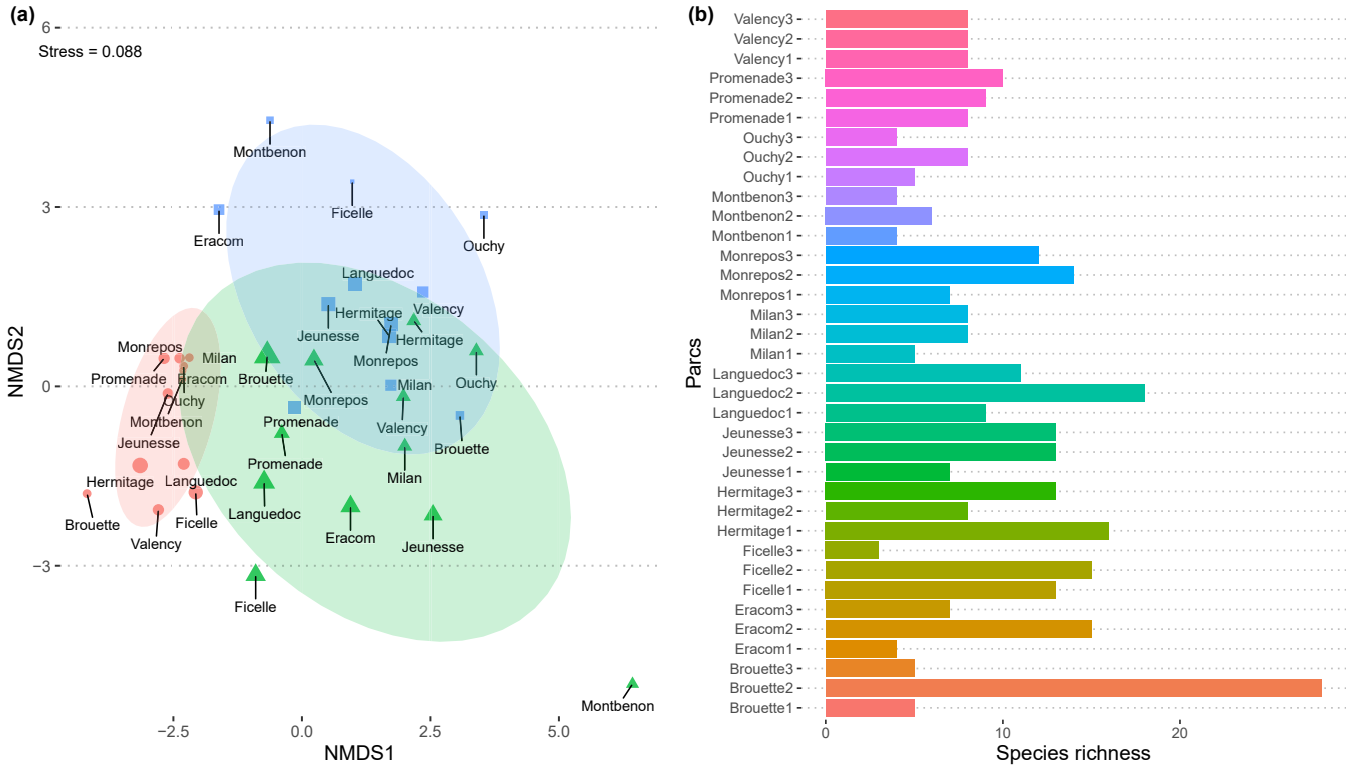

FIGURE 1 Vegetation structure and diversity across Lausanne's urban parks. (A) Nonmetric multidimensional scaling (NMDS, Bray–Curtis) of vegetation presence/absence across 36 plots (12 parks × 3 strata: herb (1, pink ellipse), shrub (2, green ellipse), tree (3, blue ellipse)), showing compositional differences among parks and vertical layers (red circles = herb, green triangles = shrub, and blue squares = tree). Points are plot values, and point sizes represent scaled plot-level plant species richness. (B) α-diversity (species richness per plot) by stratum (1 = herb, 2 = shrub, 3 = tree); bars show means across parks and strata. Vegetation was surveyed around volatile organic compounds (VOCs) sampling devices using concentric plots (3/5/10 m radii for herb/shrub/tree) and species recorded by stratum; diversity metrics derived from species presence per stratum (see vegetation survey). Together, panels highlight strong ecological heterogeneity across "urban green" typologies, both horizontally among parks and vertically among strata.

4.1 | Ecological and phytochemical patterns underpinning urban chemical environments

Our vegetation surveys revealed pronounced ecological heterogeneity across Lausanne's urban parks. Species composition varied strongly among sites, and vertical stratification contributed substantially to overall richness. These findings align with perspectives in urban ecology that view cities as mosaics of dynamic, mixed plant communities rather than simplified green infrastructures (Pickett et al., 2016). This has implications for how urban nature is conceived and designed. Historically, the "aesthetics of order" (Franck & Stevens, 2006) have dominated urban planning, prioritizing formal, manicured vegetation over ecologically complex plantings. Yet, our results show that different parks generate distinct structural complexities through the planting of trees, shrubs, and herbaceous layers, each contributing distinct species. Vegetation complexity has also been shown to substantially shape habitat quality, support wildlife, and influence ecosystem functions ranging from soil processes to thermal buffering (Pan et al., 2021). Recognizing vegetation as an ecological system rather than a decorative element reframes urban greening as a functional strategy, in which richer, more layered plant assemblages build environmental heterogeneity that matters both for ecological resilience and for human experience.

This structural and taxonomic diversity translated directly into chemical diversity. Airborne VOC profiles differed among parks and across vegetation layers, showing that plant identity and microenvironmental conditions create spatially distinct "chemical mosaics" (Hunter, 2016). Importantly, VOC richness increased with plant species richness, indicating that botanical diversity enhances the molecular complexity of the air encountered by park users. Simulated communities reinforced this empirical pattern. When plant richness increased in virtual assemblages, while maintaining the observed proportions of vegetation layers, chemical richness rose predictably, albeit with diminishing gains at higher levels. This consistency between empirical and simulated relationships suggests that biodiversity acts as a robust generator of chemical diversity (Schuman et al., 2016). Leaf metabolomic data further revealed phylogenetically patterned chemical potential (Defossez et al., 2021), with certain lineages such as conifers, laurels, magnolias, and Rosaceae exhibiting especially high metabolite diversity. These findings highlight opportunities for phylogenetically informed planting strategies that maximize both ecological and chemical functional diversity (Molina-Venegas et al., 2021; Srivastava et al., 2012).

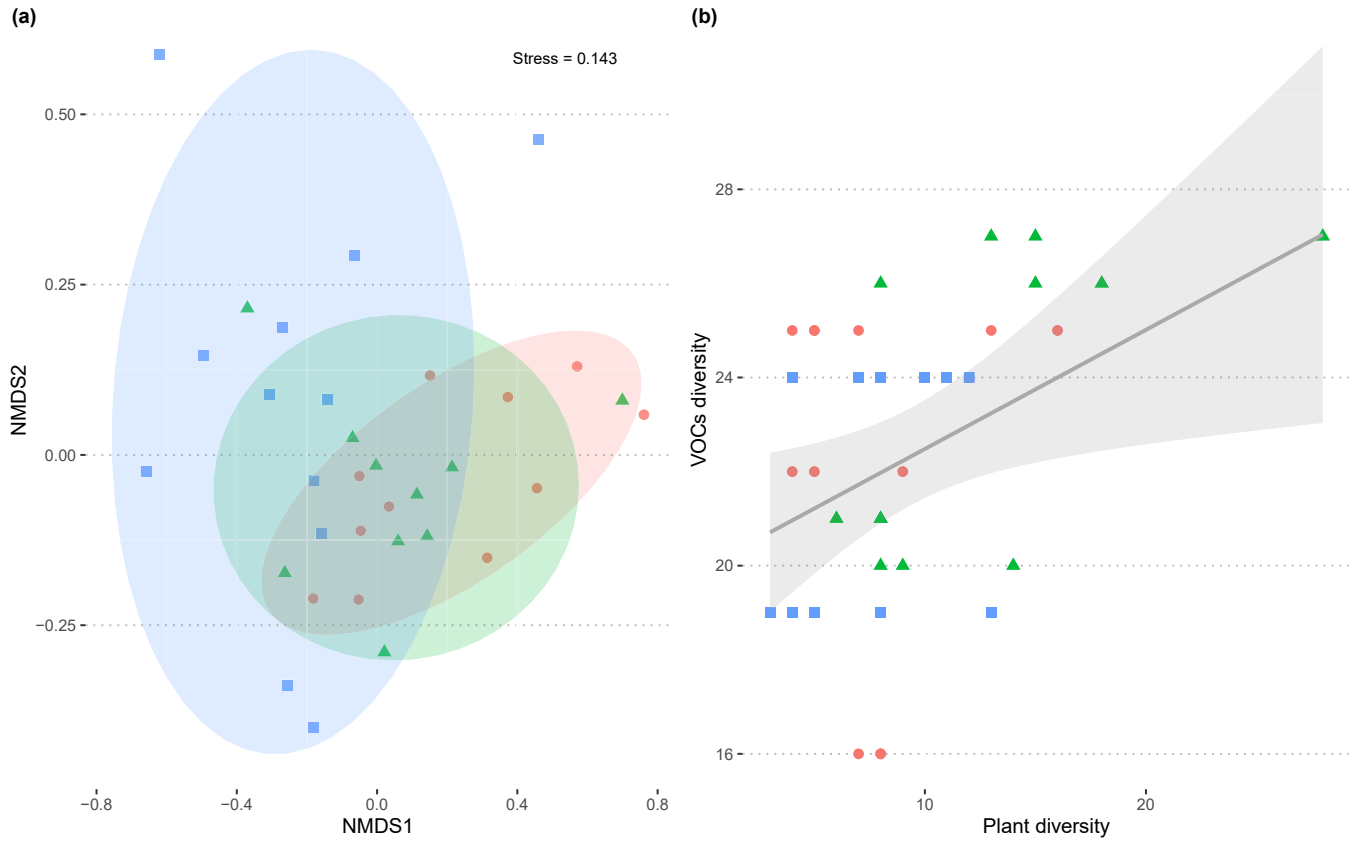

FIGURE 2 The chemical atmosphere of parks: VOC composition and diversity. (a) Nonmetric multidimensional scaling (NMDS, Bray–Curtis) of ambient volatile organic compounds (VOCs) profiles across parks, colored by vegetation layer (red circles = herb, green triangles = shrub, and blue squares = tree). VOCs were collected with portable pumps on activated-carbon tubes (≈42-L air per sample) and quantified by gas-chromatography coupled to mass spectrometry (GC–MS). (b) Relationship between plant diversity and volatile organic compounds (VOCs) richness at the park level. Each points represents a park-level summary (averaged across vegetation strata), with linear fit ±95% CI (linear model; $R^2 = 0.15$, P = 0.020). Results indicate that parks differ in their "chemical signatures," and that botanical richness is a useful predictor of airborne chemical richness relevant to human exposure.

4.2 | From chemical complexity to human well-being: Beyond physical attributes of vegetation

While the benefits of green space for health and psychological restoration are well established, the mechanisms underlying these effects remain incompletely understood (Zhang et al., 2017). The sensory and biochemical dimension revealed here (i.e., biodiverse vegetation enriches the ambient phytochemical environment) adds an important layer to the nature–health relationship. Forest environments provide strong evidence that inhaling plant volatiles can reduce cortisol, lower blood pressure, improve mood, or modulate immune function (Cho et al., 2017; Masyita, Mustika Sari, et al., 2022; Zorić et al., 2022). Laboratory and clinical studies suggest that even low concentrations of specific volatiles can influence cognitive and emotional regulation (Ikei et al., 2015; Kim et al., 2019). Our findings show that urban parks, far from being chemically impoverished approximations of forests, harbor meaningful phytochemical variation tied directly to biodiversity. This suggests that everyday urban experiences, such as walking under mixed canopies, resting near flowering shrubs, or simply inhabiting biodiverse parks, may provide subtle sensory and physiological benefits. Such exposures may be particularly important for residents who rarely access more remote natural areas. In this view, urban nature is an authentic setting for human–plant interactions, where biodiversity shapes not only what people see but also what they breathe and feel.

4.3 | Toward a functional framework for urban planning

Our results offer a foundation for rethinking urban planning through a functional, biodiversity-driven framework that recognizes vegetation not only as structural or aesthetic infrastructure but also as a generator of chemical, ecological, and health-relevant qualities. The demonstrated link between vegetation complexity and phytochemical richness has several implications for how cities design green spaces. First, species selection and botanical diversity matter. Urban planting schemes often rely on a narrow subset of ornamentals or fast-growing species; however, our findings show that diverse and phylogenetically broad species assemblages generate richer chemical

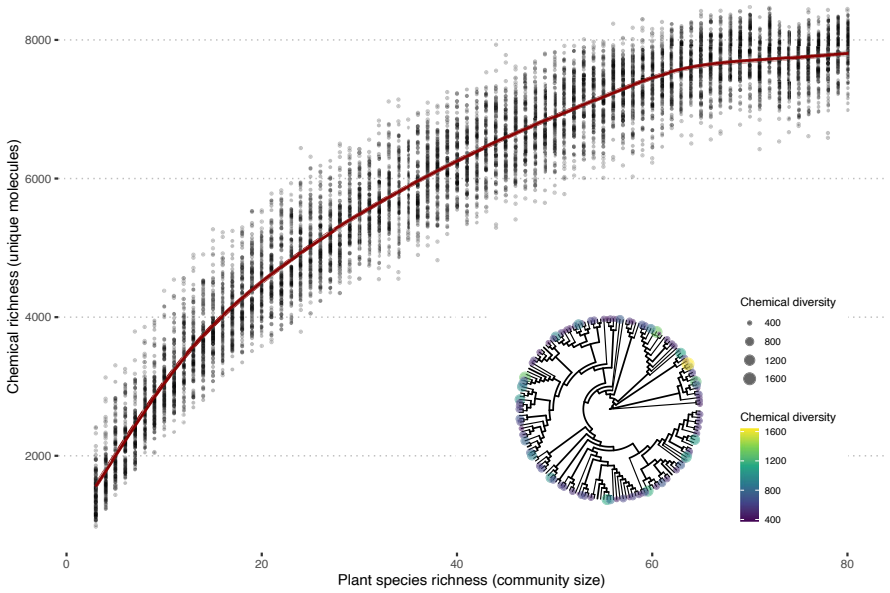

FIGURE 3 Community–phytochemical diversity coupling and phylogenetic context. Simulated communities assembled from the observed species pool (stratified by empirical layer proportions: herb 0.358, shrub 0.328, and tree 0.313) reveal a positive richness–chemistry relationship. Main panel: chemical richness (union of unique molecules across species; liquid chromatography coupled to mass spectrometry [LC–MS] feature presence/absence) increases with plant species richness in virtual communities (sizes 3–80; 100 replicates per size). Red line shows LOESS smoother. Inset: circular phylogeny of sampled species with tip points scaled and colored by per-species chemical diversity (LC–MS features), indicating clade-level variation in metabolite breadth. Together, these analyses show that richer plant assemblages generate richer bioactive chemical environments, offering a mechanistic link between urban biodiversity and molecular ecosystem services.

environments that may support mental and physical well-being. Incorporating a wider array of taxa, including lineages with high chemical potential, can enhance both ecological resilience and sensory richness. Second, structural complexity matters. Multilayered vegetation (trees, shrubs, and herbaceous layers) produced more diverse chemical profiles than simplified plantings. This underscores the value of designing parks, campuses, and streetscapes with three-dimensional vegetation structure that supports ecological functions, pollinators, and habitat heterogeneity (Randlkofer et al., 2010). Such designs also align with evidence that perceived configurational heterogeneity supports psychological restoration (Meyer-Grandbastien et al., 2020). In this sense, phytochemical diversity can be understood as a cobenefit of ecological complexity, a molecular expression of biodiversity that enhances environmental quality and human experience. Third, chemical diversity itself can be considered an ecosystem service (Epps et al., 2007; Quijas et al., 2010). Integrating chemical functional traits into planning tools, alongside canopy cover, species richness, or habitat metrics, offers a more holistic understanding of how green spaces contribute to health and sustainability. Such integration is particularly relevant for municipalities aiming to embed public health objectives in urban greening policies.

At the same time, translating this framework into practice requires acknowledging the limitations of our study. First, sampling was conducted during a single period, which does not capture seasonal variability in VOC emissions. While our sampling design captures vertical differences in vegetation structure and associated chemical environments, we acknowledge that using a single sampling location per stratum per park does not fully represent within-park heterogeneity. This approach reflects a trade-off between spatial replication and the logistical constraints of time-integrated VOC sampling and was designed to prioritize comparability across parks and relevance to typical visitor exposure. In addition, land-use and land-cover characterization was restricted to park boundaries and thus does not explicitly account for the influence of surrounding urban context on local air chemistry or perception. Future studies could expand both temporal and spatial replication and incorporate buffer-based approaches to better resolve these effects. Finally, urban scentscapes are shaped by ventilation patterns, microclimates, and pollutant interactions that warrant further investigation. Equity considerations also remain crucial. If chemical richness contributes to well-being, then making biodiverse, chemically rich green spaces accessible across all neighborhoods becomes an issue of environmental and social justice (Przewoźna et al., 2024; Wolch et al., 2014). Complementary participatory research could deepen understanding of how residents perceive, value, and benefit from the olfactory and sensory qualities of urban nature.

In summary, our findings support a functional framework in which planning for botanical and structural diversity also means planning for chemical and sensory diversity, an underrecognized dimension of nature-based solutions. Designing cities that intentionally foster ecological and phytochemical richness offers a promising pathway for building healthier, more resilient, and more equitable urban environments where both people and plants can thrive.

AUTHOR CONTRIBUTIONS

Aurora Ruggeri, Ola Söderström, and Sergio Rasmann conceived the idea and designed the experiment. FBF, with the support of Aurora Ruggeri, Gaetan Glauser, Gregory Röder, and Sergio Rasmann, performed the experiments and collected the data. Sergio Rasmann, with the support of FBF and Aurora Ruggeri, analyzed the data. Aurora Ruggeri wrote the first draft of the manuscript. All authors edited and agreed on the last version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILIABILITY STATEMENT

All the data and the code are stored on the data repository OSF (https://doi.org/10.17605/OSF.IO/U2TPH).

ORCID

Aurora Ruggeri https://orcid.org/0009-0004-4848-1058
Fethi Ben Fraj https://orcid.org/0000-0001-6566-9344
Gaetan Glauser https://orcid.org/0000-0002-0983-8614
Gregory Röder https://orcid.org/0000-0002-7110-294X
Ola Söderström https://orcid.org/0000-0002-7111-8765
Sergio Rasmann https://orcid.org/0000-0002-3120-6226

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SUPPORTING INFORMATION

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