Multi-Species Prototypes for Sustainable Environments

How does a living wall design affect air pollution in a typical street section?

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This paper studies the effect of trees and living walls designs in the urban environment, as a measure for increasing biodiversity and enhancing urban air quality. The chosen location is a neighborhood plot in the Mediterranean climate of Tel Aviv, with vibrant pedestrian activity. Simulations are performed using the urban pollution dispersion tool in ENVI-met, for a high-traffic and a low-traffic inner city road, with a focus on airborne particle matter (PM) concentrations. Results depict a winter day that air quality standards were moderate. The different scenarios, with and without trees, and different % of living wall designs and vegetative volumes brought about considerable reductions in airborne PM concentrations. However, the reductions still failed to reach WHO recommended air quality standards. Results point out towards a more holistic framework of green infrastructure strategies that may also include green walls, bicycle routes, less vehicle access, and more.

Keywords: *Urban neighborhood, Living Walls, PM concentration, ENVI-met.*

INTRODUCTION

Current high levels of urban air pollution result in considerable consequences to the health of both humans and the various ecosystems (EEA European Environmental Agency, 2019). At the same time the increase of global population, urbanization, and the design of dense urban centers, affect land transformations, including the biodiversity of ecosystems (Savard, Clergeau and Mennechez, 2000). In terms of urban ecosystems, there are questions on what conditions can cities create for species to survive, and which ones actually do (Sweet *et al.*, 2022). Varying green infrastructure (GI) urban strategies, such as green patches, parks, and meadows, offer valuable spaces for biodiversity (Goddard, Dougill and Benton, 2010). However, increasing urbanization dictates for more ecologically driven opportunities within the urban fabric (CBD, 2012). In that respect, the incorporation of green roofs (GR) and living walls (LW) in buildings, in dense urban centers, can offer multiple environmental benefits.

Outdoor air pollution is one of the most threatening urban pollutants on public health and animal welfare (Mukherjee and Agrawal, 2017; Torres-Blas *et al.*, 2023). It is largely assigned to airborne particulate matter (PM) concentrations that are a mixture of solids and aerosols, described by their diameter. PM_{10} particles have a diameter of 10 microns or less, and are mainly coarse particles of smoke, dust, and heavy metals. $PM_{2.5}$ are fine particles of 2.5 microns or less in diameter, and consist largely of aerosols, smoke, and fumes. Both concentrations are mainly attributed to urban traffic. In most cities around the world, PM levels exceed World Health Organization (WHO) guidelines, that also become more strict with time. According to WHO 2022 24-hour target, recommended PM_{10} concentrations are 50 µg/m^3 and $PM_{2.5}$ concentrations are 25 µg/m^3 (Geneva: World Health Organization, 2021; World Health Organization, 2022).

In this research paper we focus on the reduction of PM particles (PM_{10} and $PM_{2.5}$) as the highest air pollution health-related parameter within the urban fabric (Chow *et al.*, 2006). Vegetation and soil, are able to absorb a variety of pollutants from the air (Barwise and Kumar, 2020), while some plant species are more successful in mitigating air pollution than others (Viecco *et al.*, 2018). However, the effect of soil, as discussed later in the paper , was not possible to be evaluated currently. We study the reduction of PM air particles through the presence of trees and LW systems within a typical urban neighborhood design in the Mediterranean climate, using ENVI-met simulations. We then evaluate through the studies made, the effect of GI on urban air quality that is an important parameter for all living systems. Results can be used for interdisciplinary future studies in the evaluation of "biodiversity and LW systems", as part of correlations between architecture and ecology, towards multi-species urban environments. Selvan et. al. (2023) presented initial computational methods to comprehend the influence of vegetation on building envelopes in the urban environment (Selvan; et al., 2023).

Figure 1
View of high-traffic inner city road within proposed urban plot. The photo was intentionally taken during a quiet moment

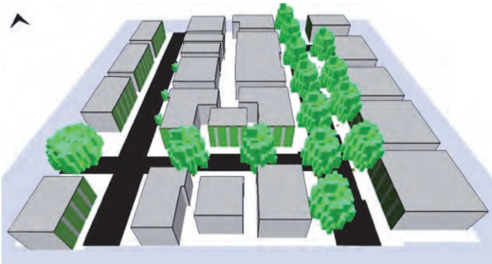

Figure 2
3D simulation model representation of the urban neighborhood with LW design

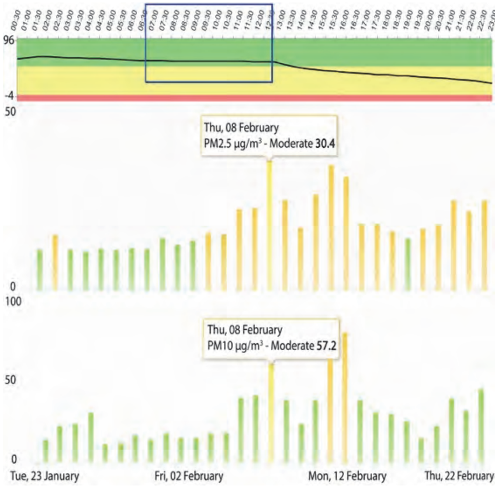

Figure 3
Simulation data, ref. https://air.sviva.gov.il/

METHODOLOY

The chosen location is the city of Tel Aviv , a coastal city in Israel. The proposed site is an urban plot in the city center, comprised by a high-traffic inner city road, and low-traffic adjacent streets, see figures 1 and 2. This is a residential neighborhood, with a variety of shops, bars, and restaurants on either side of the main road that has a vibrant pedestrian activity. Tel Aviv's Mediterranean climate is mild with annual averages fluctuating around 20 °C. Annual relative humidity values are high, with averages between 60-67%. The month of January records the lowest daily temperature of about 13°C. Inner city wind velocities are recorded between 0.5-2.5 m/sec, while wind speed is lower in the beginning of the day and increases as time goes by. Climatic variables affect the dispersion of pollutants in the atmosphere, with the higher concentrations been recorded until about mid-day, see Figure 3.

Pollution mitigation studies help to understand better urban pollutant dispersion, and to develop green infrastructure (GI) strategies for improving air quality. Current studies are based on simulations, using the 'pollution dispersion' model in ENVI-met. ENVI-met is a three-dimensional non-hydrostatic model that is able to simulate the interactions between soil, vegetation , and the atmosphere (Bruse and Fleer, 1998). The program uses Leaf Area Density (LAD) profiles to calculate the dispersion and disposition of different pollutants.

Viecco et al. (2021) studies on air pollution in Santiago , Chile, showed good correlations between ENVI-met and monitored data (Viecco *et al.*, 2018). They underlined the importance of LW in the reduction of PM concentrations near street level, which is also the focus of this paper. In this study, simulations take place during a 'moderate' air quality index (AQI) status in Tel Aviv. The presence of trees and the design of LW in mitigating air pollution is studied in relation to the following scenarios:

- Scenario_1: current urban condition with trees
- Scenario_2: urban condition without trees
- Scenario_3: current urban condition with trees and proposed 60% LW 0.50cm thick vegetation
- Scenario_4: current urban condition with trees and proposed 80% LW 1.50m thick vegetation

Simulation parameters

For the design of the simulation model, we used the Open Street Map (OSM) option in ENVI-met and depicted as close as possible the location and height of trees, building heights, and surface materials. We choose 8th of February 2024, as one of the worst performing days for accumulation of PM air particles in recent days. In addition, air quality deteriorates during winter in the city, as weaker winds assist in the accumulation of pollution in the lower boundary levels of the city's canyons. On the day, the average PM_{10} concentrations were 57.2 μg/m^3, while $PM_{2.5}$ concentrations were 30.4 μg/m^3, exceeding the target of 50 μg/m^3 for PM_{10} and 25 μg/m^3 for $PM_{2.5}$, respectively. The higher concentrations were recorded between the morning hours until about mid-day, see figure 3. PM concentrations were used as inputs in the simulations that run between 07:00-13:00hrs. See table 1 for all simulation parameters.

Considering the LW design on the building envelope, the proposed configuration presents the available wall surface of buildings after excluding windows and doors, see figure 2. The studies included two scenarios, one with 60% of LW envelope area 0.50cm thick vegetation, and another with 80% of LW area 1.50m thick vegetation.

In addition, all building heights are estimated at an average of 10m high. This simplification made sense since the focus of this study is on PM

Table 1
Simulation parameters

Location	Tel Aviv, Israel
Simulation date	8th of February
Simulation time	6 hrs. per day : 7:00 – 13:00
Domain size	160m x 160m
Grid resolution	1m x 1m x 1m (x,y,z) / dz lowest grid box is spit into 5 cells
Average building height	10 meters high
Climate data	ISR_Tel.Aviv-Bet.Dagan.401790_MSI.epw
Surfaces	Concrete buildings with moderate insulation, gray concrete pavement, loamy soil, asphalt road
3D plant type	H: 16m, D: 10m; H:5m, D: 3m
High-traffic inner city road	DTV: 8000; No. of lanes: 2
Low-traffic inner city road	DTV: 800; No. of lanes: 1
PM concentrations	$PM_{2.5}$ = 30.4 μg/m^3 PM_{10}= 57.2 μg/m^3

concentrations close to street level, at 0.90m high. Cars' exhaust is estimated to be at about 0.30m high, while pedestrian street level is at 1.50m high. The proposed 0.90m refer to people sitting on the side of the road, at benches and chairs, to young children, as well as urban dogs. Data input in relation to air pollution sources and Daily Traffic Value (DTV) are described through the sources tool in ENVI-met. DTV values of the two types of streets present in the model, the high-traffic inner road and the low-traffic inner road, are relative to the data presented from Israel's Ministry of Transportation.

Simulation limitations

ENVI-met provides the possibility of designing a LW through the 'Greenings' tab in DB Manager, however, currently, its implementation has no effect on the accumulation of pollutants. The program does provide, however, an air-pollution analysis through the LAD profile in the vegetation tool. So, in order to check the effect of LW on the reduction of pollutants within the urban environment, a simpler design was created. This meant that the proposed LW were described and simulated without the option of a soil substrate behind the greening layer. This restriction, however, was also in line with the program's limitation in simulating the effect of pollution accumulation within a soil substrate.

Furthermore, PM removal is analogous to the interactions of particles with the plant morphological properties, including their shape, size, and orientation. Petroff et al. (2008) revealed that optimum particle removal capacities exist in plants with small leaves (Petroff et al., 2008). Leaf area index (LAI) is a further characteristic in species capabilities to remove particles, with large gaps between leaves resulting in lower levels of particles absorption (Leonard, McArthur and Hochuli, 2016). Udeshika Weerakkody et al. (2017) research on the PM capture capabilities of leaves concluded that smaller leaved species with a high LAI have the higher PM removal potential.

In our current ENVI-met simulations, however, we faced numerous restrictions with providing detailed specifications on the design of the LW's vegetative layer. The program does provide the option to construct your own vegetative layer morphology, but the options are still either too general or require specialized knowledge not easily obtained. We do feel, nevertheless, that for the purpose of this publication the required aim has been achieved.

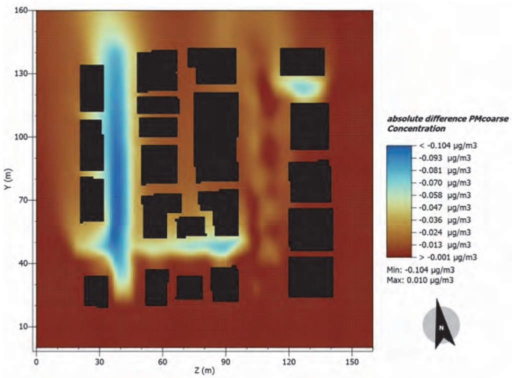

Figure 4
Reduction of PM10 concentrations_A

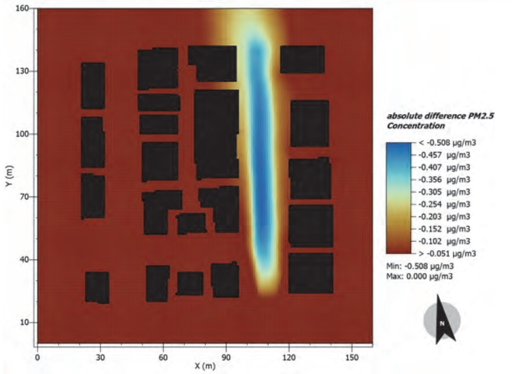

Figure 5
Reduction of PM2.5 concentrations_A

RESULTS

The mitigation of air pollution is evaluated through the improvement of air-quality by the reduction of PM particles. Two types of results are presented here. First, we look into the effect of trees and LWs on the

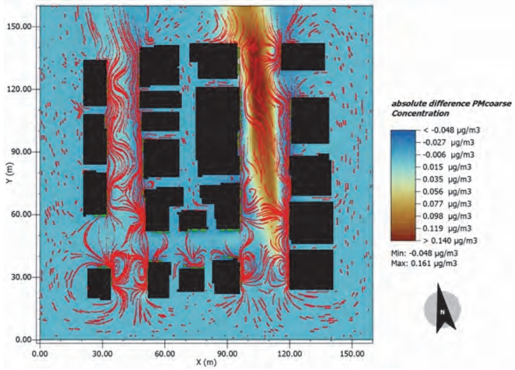

Figure 6
Reduction of PM10 concentrations_B

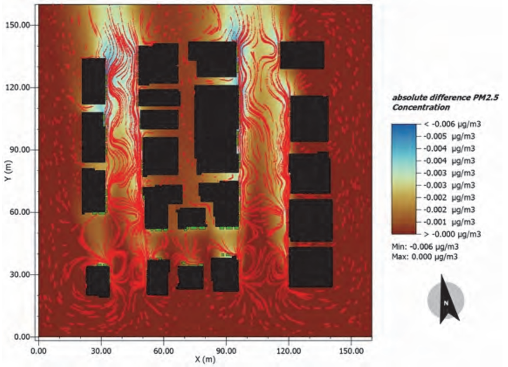

Figure 7
Reduction of $PM_{2.5}$ concentrations_B

reduction of PM concentrations within the urban canyons. We then evaluate PM concentration reductions in the areas adjacent to the LWs.

PM concentrations in the urban canyons

In this set of results, we use the compare 2D option in ENVI-met, where data between two scenarios are compared to each other. The variables here are the PM coarse concentration µg/m^3 (PM_{10}) and the $PM_{2.5}$ concentration µg/m^3. Results are presented below:

A. Comparison of Scenario_1: current urban condition with trees with Scenario_2: urban condition without trees, at 12:00pm

Results evaluate the effect of trees, by simulating the current urban configuration with and without them, while using as an input measured PM particle data, during a winter day. Literature review points out that in dense urban canyons the presence of trees may reduce the capacity of air to circulate and mix, and thus disperse pollutants (Wania *et al.*, 2012). Current results during moderate air quality conditions, show slight reductions in both PM_{10} and $PM_{2.5}$ concentrations. PM_{10} reductions are up to 0.1 µg/m^3 and take place along the low-traffic inner city road. $PM_{2.5}$ reductions are up to 0.5 µg/m^3 and are depicted along the area of the high-traffic inner city road, see figures 4 and 5. The importance of trees is especially noted on the reduction of $PM_{2.5}$ concentrations that accumulate mainly as a result of urban traffic. However, the greatest $PM_{2.5}$ reductions are presented along the high-traffic road, underlining both the effect of air circulation due to the movement of cars, as well as due to the presence of trees on either side of the road.

B. Comparison of Scenario_1: current urban condition with trees with Scenario_3: current urban condition with trees and proposed 60% LW 0.50cm thick vegetation, at 12:00pm

Results depict the effect of LW systems in the enhancement of urban air quality. The disposition of PM particles is presented in relation to wind velocities. In these set of results the reductions of PM_{10} particles are greater than the reduction of $PM_{2.5}$. PM_{10} values reach 0.048 µg/m^3 less in the areas adjacent to the high-traffic inner city road, while the accumulation of particles along the middle of the road is potentially worse. On the other hand, the reduction of $PM_{2.5}$ particles as a result of the presence of LW within the urban canyons, are minimum. However, there are clear correlations between wind velocity trends and $PM_{2.5}$ concentrations, while the greater reductions are portrayed in the areas adjacent to the LWs, see figures 6 and 7.

C. Comparison of Scenario_1: current urban condition with trees with Scenario_4: current urban condition with trees and proposed 80% LW 1.50m thick vegetation, at 12:00pm

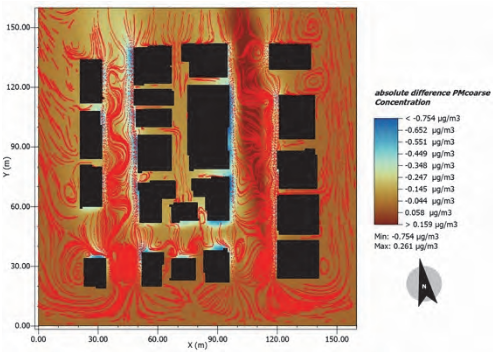

Figure 8
Reduction of PM_{10} concentrations_C

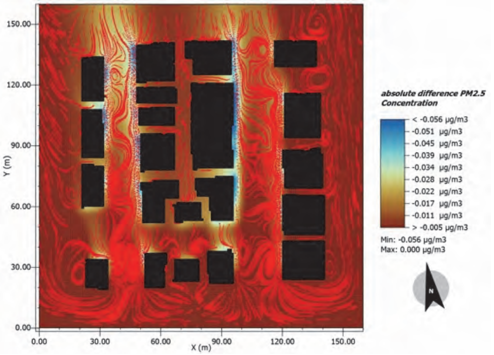

Figure 9
Reduction of $PM_{2.5}$ concentrations_C

In Scenario_4 the LW design covers 80% of the building envelope and has a 1.50m thick layer of vegetation. These increases in comparison to Scenario_3 brought further decreases in both $PM_{2.5}$ and PM_{10} concentrations, see figures 8 and 9. The reductions from the existing condition of Scenario_1 reach 0.754 µg/m^3 less for PM_{10} , while there are clear indications that the areas near the LW present better results. The increase of the % of the LWs, as well as of the vegetative volume, have a greater effect in $PM_{2.5}$ concentrations from the results of Scenario_3. Reductions reached 0.056 µg/m^3 less than Scenario_1, while it is obvious that these mainly relate to the areas close to the LW. In the following section we examine in further detail the reductions of PM particles between scenarios 1 and 4 at a distance of about 1m away from the LWs.

PM concentrations adjacent to the LW

In order to understand better the effect of LW on enhancing urban air quality near ground level, another set of results is presented here with data extracted at a distance of approximately 1m away from the LWs. The graphs depict the reductions in PM concentrations between the existing condition of Scenario_1, simulated with the monitored PM values, and proposed Scenario_4 that presented the optimum results. The graphs depict in greater detail that PM_{10} concentration reductions are much more pronounced than $PM_{2.5}$, see figures 10 and 11.

DISCUSSION

According to WHO 24-hour target recommended PM_{10} concentrations are 50 µg/m^3 , while the measured value for the 8th of February was 57.2 µg/m^3 . So, a reduction of 0.5 µg/m^3 due to the LW design, can be considered substantial towards the initial objective to mitigate air pollution, see figure 10. On the other hand, WHO recommended $PM_{2.5}$ concentrations are 25 µg/m^3 , and the monitored values were 30.4 µg/m^3 . In that respect, reductions in the range of 0.05 µg/m^3, are minimum, see figure 11. Nevertheless, the studies revealed correlations between wind direction and velocity, with the accumulation of $PM_{2.5}$ particles. However, more studies are required to understand better the behavior of $PM_{2.5}$ concentrations within the urban fabric and optimum strategies towards their dispersion.

CONCLUSIONS

This research paper focused on the mitigation of air pollution that has become a serious environmental risk on a worldwide scale. It draws upon literature review that green infrastructure assists towards the enhancement of urban air quality and studied the

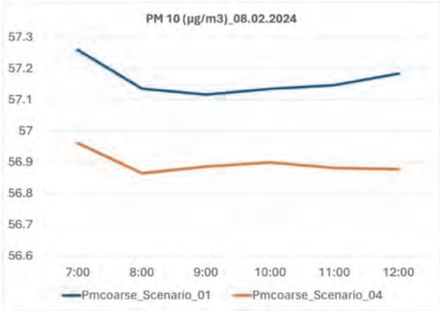

Figure 10
PM2.5 concentrations between scenarios 1 and 4

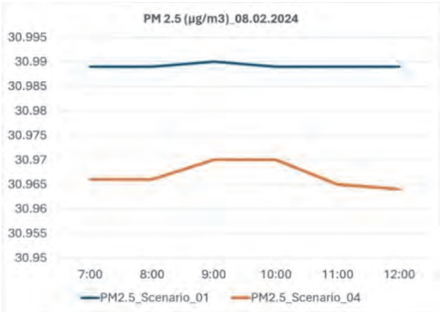

Figure 11
PM10 concentrations between scenarios 1 and 4

effect of trees and LW on the reduction of PM particle concentration. The studies are based on ENVI-met simulations of a vibrant neighborhood plot in Mediterranean climate of Tel Aviv, Israel. However, results are also applicable to other cities with similar climates, not least the Middle East and Mediterranean basin.

Simulations use monitored PM particle values during a moderate air quality index day. Despite the limitations we faced describing accurately the vegetative layer of the LW systems, results give a good indication of the importance of trees and LW in mitigating air pollution. PM_{10} concentrations reached approximately a 0.5% decrease, while $PM_{2.5}$ concentrations were only reduced by a 0.08%. However, more studies are needed on the effect of GI strategies and PM particle concentration reduction, while special emphasis was given on the relationship between $PM_{2.5}$ and wind behavior. For a more holistic understanding on the topic, further simulations, as well as the implementation of empirical studies, for a deeper understanding of the ecological, biodiversity implications, become vital (Selvan; *et al.*, 2023).

Initial results point towards GI strategies that promote air circulation within the urban canyons, and reduce PM concentrations through the plants PM capture abilities. The inclusion of LW as part of building envelope design, is potentially an important strategy, however, is not sufficient within the already highly polluted urban environments. In that respect, a combination of LWs and GRs, may bestow a more positive outcome, with GR been positioned at relative low heights in order to have an effect on street level, according to literature review. Further urban design strategies, like the careful positioning of trees and other low-rise vegetation to allow for air circulation, also play a vital role in the enhancement of urban air quality.

Supplementing the above, a more holistic approach and resolution of the issue at hand, would look into a combination of building design and urban design strategies. Such proposals could incorporate the design of wider pavements, bicycle paths, fewer vehicle lanes, more pedestrian routes, as well as other possible solutions. Some of these strategies are slowly been implemented along different areas on the same high-traffic road used in the current study, as part of the Tel Aviv Minicipality actions on Environment and Sustainability. The aim is towards more green, more quiet, and hopefully less polluted cities that provide also possibilities for more plant and animal species to live and flourish. Considering the rate of urbanization, global population, biodiversity loss, and climate change, the above discussed topics are tangible matters, and their importance towards urban resilience, vital.

REFERENCES

Barwise, Y. and Kumar, P. (2020) 'Designing vegetation barriers for urban air pollution abatement: a practical review for appropriate plant species selection', *npj Climate and*

Atmospheric Science, 3(1), p. 12. doi:10.1038/s41612-020-0115-3.

Bruse, M. and Fleer, H. (1998) ‘Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model’, *Environmental Modelling & Software*, 13(3–4), pp. 373–384. doi:10.1016/S1364-8152(98)00042-5.

CBD (2012) *Cities and Biodiversity Outlook: A Global Assessment of the Links between Urbanization, Biodiversity, and Ecosystem Services*, *Executive Summary*. doi:doi:10.6084/m9.figshare.99889.

Chow, J.C. *et al.* (2006) ‘Health Effects of Fine Particulate Air Pollution: Lines that Connect’, *Journal of the Air & Waste Management Association*, 56(10), pp. 1368–1380. doi:10.1080/10473289.2006.10464545.

EEA European Environmental Agency (2019) *Air quality in Europe — 2019 report*, *EEA Report No 10/2019*. doi:10.2800/822355.

Geneva: World Health Organization (2021) ‘WHO global air quality guidelines’, *Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*, pp. 1–360.

Goddard, M.A., Dougill, A.J. and Benton, T.G. (2010) ‘Scaling up from gardens: biodiversity conservation in urban environments’, *Trends in Ecology and Evolution*, 25(2), pp. 90–98. doi:10.1016/j.tree.2009.07.016.

Leonard, R.J., McArthur, C. and Hochuli, D.F. (2016) ‘Particulate matter deposition on roadside plants and the importance of leaf trait combinations’, *Urban Forestry & Urban Greening*, 20, pp. 249–253. doi:10.1016/j.ufug.2016.09.008.

Mukherjee, A. and Agrawal, M. (2017) ‘World air particulate matter: sources, distribution and health effects’, *Environmental Chemistry Letters*, 15(2), pp. 283–309. doi:10.1007/s10311-017-0611-9.

Petroff, A. *et al.* (2008) ‘Aerosol dry deposition on vegetative canopies. Part I: Review of present knowledge’, *Atmospheric Environment*, 42(16), pp. 3625–3653. doi:10.1016/j.atmosenv.2007.09.043.

Savard, J.P.L., Clergeau, P. and Mennechez, G. (2000) ‘Biodiversity concepts and urban ecosystems’, *Landscape and Urban Planning*, 48(3–4), pp. 131–142. doi:10.1016/S0169-2046(00)00037-2.

Selvan; *et al.* (2023) ‘Multi-species building envelopes: Developing a multi-criteria design decision-making methodology for cohabitation’, in *Human-Centric. 28th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2023, 2, March, 645–654*.

Sweet, F.S.T. *et al.* (2022) ‘Data from public and governmental databases show that a large proportion of the regional animal species pool occur in cities in Germany’, *Journal of Urban Ecology*, 8(1), pp. 1–10. doi:10.1093/jue/juac002.

Torres-Blas, I. *et al.* (2023) ‘Impact of exposure to urban air pollution on grey squirrel (Sciurus carolinensis) lung health’, *Environmental Pollution*, 326(February), p. 121312. doi:10.1016/j.envpol.2023.121312.

Viecco, M. *et al.* (2018) ‘Potential of particle matter dry deposition on green roofs and living walls vegetation for mitigating urban atmospheric pollution in semiarid climates’, *Sustainability (Switzerland)*, 10(7). doi:10.3390/su10072431.

Wania, A. *et al.* (2012) ‘Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations’, *Journal of Environmental Management*, 94(1), pp. 91–101. doi:10.1016/j.jenvman.2011.06.036.

World Health Organization (2022) *Ambient (outdoor) air pollution*, *WHO*. Available at: https://www.who.int/ (Accessed: 15 December 2023).

During the 2020s and beyond, the field of computational design and fabrication will face a number of new challenges and opportunities offered by Artificial Intelligence (AI) and Machine Learning (ML). These technologies represent a new era of data-driven intelligence, which is steadily gaining increasing influence in other fields, but as yet has had little impact in architecture. At the core of this new technological shift, data will be collected, processed, shared, and used as a decision-making tool to resolve a multitude of social, economic, and environmental issues.

In view of this paradigm shift, the conference attempts to provide the ground for presenting and discussing possibilities offered by data-driven intelligence across a range of thematic areas. These diverse themes might in turn influence and provide the ground for reconsidering architectural knowledge and practice in the future. In parallel, the conference attempts to critically reflect upon, discuss and question the future of applying data-driven intelligence in architectural knowledge and practice. What are the risks posed by the use of data-driven intelligence in architecture? In this new era, what will the role of architects be? Does this mark the beginning of a reconsideration of the way architects participate in the creation of knowledge and practice, or will it bring about their marginalisation? What will the social, economic, and environmental impact of data-driven intelligence be?

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