PROSTOR

31 [2023] 1 [65]

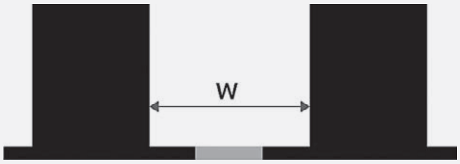
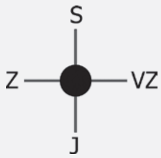
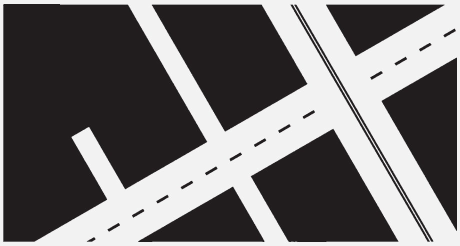
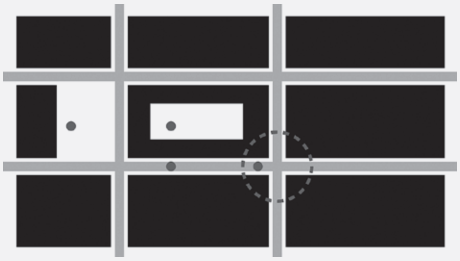
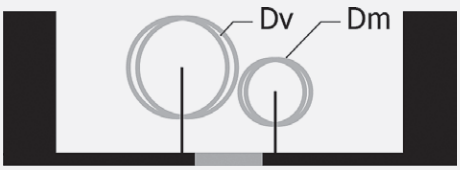
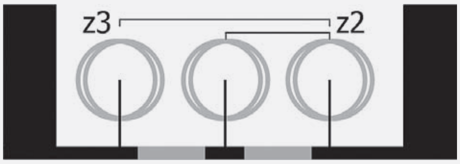
A SCHOLARLY JOURNAL OF ARCHITECTURE AND URBAN PLANNING
ZNANSTVENI ČASOPIS ZA ARHITEKTURU I URBANIZAM

UNIVERSITY OF ZAGREB FACULTY OF ARCHITECTURE
SVEUČILIŠTE U ZAGREBU ARHITEKTONSKI FAKULTET

ISSN 1330-0652
https://doi.org/10.31522/p
CODEN PORREV
UDC 71/72
31 [2023] 1 [65]
1-138
1-6 [2023]

Af

Table I Modelling domains and categorisation of variable classes

Domain	Category	Scheme	Description	Class
Built environment – morphology	Street canyon height/width ratio		The height of the buildings (h) and the width of the street (w) form the street canyon ratio H/W. Street canyons are classified in three classes.	model 20/50, H/W 0.4
				model 20/30, H/W 0.6
				model 20/20, H/W 1
	Orientation of the street grid		The main street, and the development of which the school building is a part, can be divided into two predominant orientations.	Wind direction perpendicular to the street grid
				Wind direction parallel to the direction of the street grid
The Open space	Typology of the thoroughfare		PM particulate pollutants for three categories of traffic routes	Main road, collector road, local road
	Position within the street grid		The position within the street grid is defined a ccording to the windward or leeward side, the side, the proximity to the intersection and the location at the edge or within the domain unit.	Windward or leeward
				Proximity and distance to the junction
				Position at the edge or inside the unit
Street greenery	Type of tree canopy and planting method	 	Street greenery is modelled in high and low planting modes. High and low trees are distinguished, as well as two- and three-row tree plantations.	High crown trees/1d
				Low crown trees/2d
				High crown trees/two-lane
				Low crown trees/two-lane

Kristijan Lavtižar[1], Alenka Fikfak[2], Janez P. Grom[3]

[1] University of Ljubljana, Faculty of Architecture, Zoisova 12, 1000 Ljubljana, Slovenia
orcid.org/0000-0001-8816-9764

[2] University of Ljubljana, Faculty of Architecture, Zoisova 12, 1000 Ljubljana, Slovenia
orcid.org/0000-0003-2064-0016

[3] University of Ljubljana, Faculty of Architecture, Zoisova 12, 1000 Ljubljana, Slovenia
orcid.org/0000-0001-6738-4094

kristijan.lavtizar@fa.uni-lj.si
alenka.fikfak@fa.uni-lj.si
janez.grom@fa.uni-lj.si

Original Scientific Paper
https://doi.org/10.31522/p.31.1(65).3
UDC 711.73:614.71
Technical Sciences / Architecture and Urban Planning
2.01.02. – Urban and Physical Planning
Article Received / Accepted: 18. 3. 2023. / 12. 6. 2023.

Dispersion of Traffic Pollutants in the Built Environment

STREET CANYON
STREET GREENERY
TRAFFIC POLLUTANTS
URBAN DESIGN
URBAN MORPHOLOGY

Environmental modelling software can be useful for evaluating design interventions and formulating strategies to achieve a specific purpose, such as providing outdoor thermal comfort. It is less commonly used in predicting the dispersion of street pollutants. The aim of this research is to test selected morphological patterns with respect to their influence on wind conditions and the transport of traffic pollutants, and to verify the results against previous studies. The objective of the research is to evaluate relations between building typology in interactions with urban atmosphere. The method utilises a wind tunnel simulation with a static line source of emissions. Experiment results show that the exposed urban morphology models display an impact on flow conditions and consequently on the dispersion of traffic pollutants. At the same time, the results highlight the importance of urban aerodynamic perspective, particularly of urban spaces that can be expected to be subject to higher traffic pollutants in terms of urban air pollution.

Introduction

Design interventions with computer modelling are increasingly recognised as one of the possible urban design solutions that can improve air quality at street level. These solutions can concern either landscaping features, such as trees, shrubs or green walls and roofs, or the form of the urban fabric itself, which refers to the morphological image of the city. The relationship between the height/width (H/W) ratio of the street profile and the transport characteristics of traffic pollutants is complex. Fluid dynamics studies (Zhong, Cai and Bloss, 2016; Abhijith et al., 2017a) explain the poorer air quality in narrow street profiles by the reduced self-cleaning capacity of the urban street canyon (UC), or the dispersion of traffic-derived pollutants above the roof level. The main mechanism in the reduced self-cleaning capacity is the vorticity factor, which is split in UC with a higher H/W ratio of the street canyon profile and is therefore less effective in mixing street air with air from the general urban background, the largest difference would therefore be expected at the pedestrian level (Chen et al., 2015). To tackle the problem of poor air quality in street canyons and near thoroughfares, some authors have addressed the issue of pollutant dispersion (Carvalho, Vilhena and Moreira, 2007; Gromke and Ruck, 2007; Abhijith et al., 2017a), and the issue of airiness and wind corridors in the city (Buccolieri et al., 2011; Ng and Chau, 2014; Huang et al., 2016) with wind tunnel simulations.

Removing and limiting traffic from cities is the most effective strategy to reduce traffic emissions, but for the purposes of this research we focus on other design-based options aimed at decreasing pollutant concentrations at street level. Rough surfaces halt air velocities, and some have begun to explore the impact of built environment density (Buccolieri et al., 2011; Shen et al., 2017), rooftop morphology (Hang et al., 2009; Huang et al., 2016), and street greenery (Sabatino et al., 2008; Hang et al., 2009; Abhijith et al., 2017a) on the dispersion process of traffic pollutants. Others have tested the variability of building morphology in simulations (Kurppa et al., 2018) and found that varying the height of buildings along the street improves ventilation, resulting in 7-9% lower average pollutant concentrations of traffic origin at the pedestrian level, the height where concentrations of traffic pollutants ($PM_{2.5}$, ultrafine particulate matter – UFP, nitrogen oxides) are proven to be the highest (Vardoulakis, Gonzalez-Flesca and Fisher, 2002). The dependence of street-level airborne particulate removal processes on meteorological conditions has been investigated by Chen et al. (2015), highlighting that relative humidity and wind speed have the greatest impact, while temperature has the smallest one. The influence of solar radiance on urban surfaces is complex and there is still much uncertainty about interactions between airflows and pollutant transport in the UC, although different heating scenarios undoubtedly influence airflows. Other studies (Crank et al., 2018; MeshkinKiya and Paolini, 2021) indicate that in the actual conditions of an urban street canyon, the effect of solar radiation on airflow is weaker than the effects of building agglomeration or airflow direction, but this effect only becomes noticeable in low wind conditions. In the summer, this process is accelerated by up to 0.7% due to warmer temperatures (Jeanjean et al., 2017).

Considering the processes of dispersion and deposition of pollutants in the urban environment therefore helps us to design spaces where the most vulnerable are protected from the highest concentrations of pollutants. It is only through these two processes that pollutants are removed from the atmosphere. The first requires good air flow, which depends on convection and surface roughness or wind barriers. Wind barriers in urban areas can be either built barriers or landscaping features, especially taller vegetation with dense canopies. The aerodynamic effects of spatial building blocks in the urban environment are more effective than the deposition process in removing pollutants from the atmosphere when it comes to particulate matter, according to the authors of previous studies (Vos et al., 2013; Jeanjean et al., 2017; Santiago, Martilli and Martin, 2017; Buccolieri et al., 2018). In the wind environment, green infrastructure is one of the most important building blocks in the study of air flows, but its role depends on the geometric characteristics of the street and interaction with the surrounding morphology (Buccolieri et al., 2011; Gromke and Ruck, 2007). Some plants act as porous bodies, influencing local dispersion patterns and helping to deposit and remove airborne pollutants (Abhijith et al., 2017; Salmond et al., 2016). However, the importance of green infrastructure in urban areas for air quality is not unambiguous, since it reduces wind speeds and the rate of air exchange, and it removes certain types of pollutants through the process of deposition on leaf surfaces as well (Santiago et al., 2017). It is therefore important to evaluate each green element within the context of its urban environment to determine their potential.

Materials and Methods

The study of UC on wind conditions and the transport of traffic pollutants was carried out in two steps. In the first phase, a preliminary selection of selected urban environments was done with the use of geomorphological data by the Surveying and Mapping Authority of the Republic of Slovenia (MOP, 2020). Different housing typologies were selected based on various spatial criteria, such as morphological design, period of development, distance from the city centre, variety of buildings, variety of external open space layout, spatial fit, shape, size, street network or connectivity, climatic comfort, and so on.

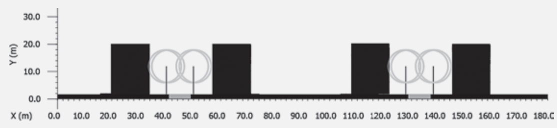
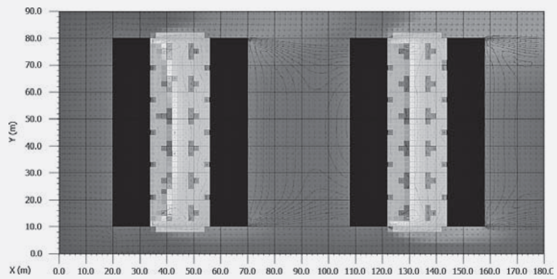
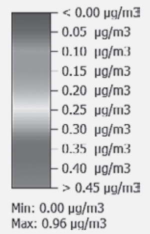
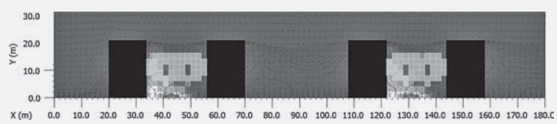
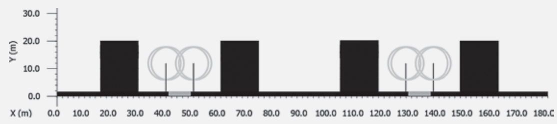
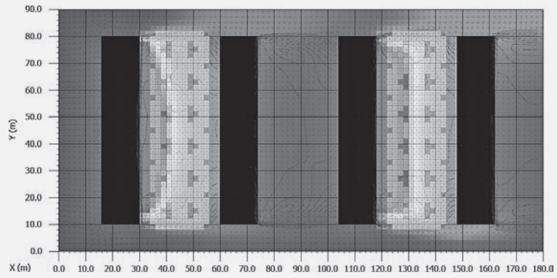
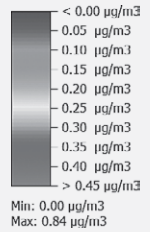
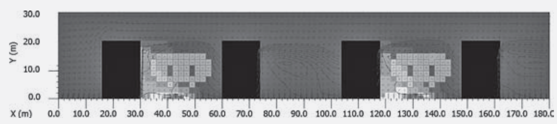
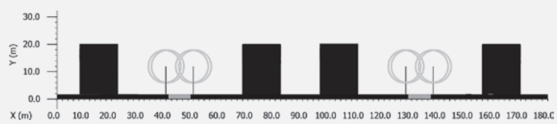
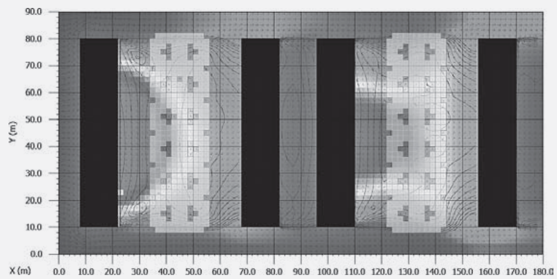
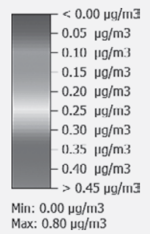
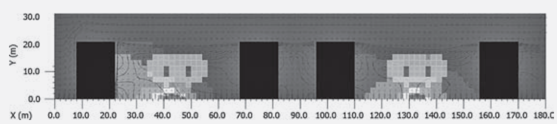
In the second phase the ENVI-met V5 software tool was used, and air quality conditions were modelled to compare spatial scenarios of urban environments. Furthermore, the input values were tested against the comparable models by the authors (Salmond et al., 2013; Abhijith et al., 2017b; Crank et al., 2018). The overarching research hypothesis of the modelling exercise is that the urban morphology and urban greenery can affect urban air quality at street level. Whether through changes to the traffic regime or spatial layout within a building, it can have a perceptible impact on indoor air quality.

The model domain included sources of CO_2, and PM_{10} and $PM_{2.5}$ pollutants. The diurnal variation of traffic emissions of particulate matter and NO and NO_2 are subject to daily changes in the number of vehicles, or depend on the daily distribution of vehicles. In other words, it is defined by traffic peak periods, with a typical increase in morning and afternoon commuting periods, which is defined as the morning and afternoon peak periods. In the research presented in this paper, two traffic distribution models were used to represent the traffic distribution typical for the city of Ljubljana (Koblar, 2016), where the daily distribution is geographically independent and represents a typical distribution for different categories of thoroughfare in the city. To further characterise the role of urban open space on the dynamics of airflows and dispersion of particulate pollutants, individual building blocks are used as models (Table I). This helps to understand how local air quality changes under different spatial scenarios by considering pollutants of transport origin. In this context, the research was focused on how this process affects the local ambient values of pollutants of transport origin in the atmosphere. The most common spatial building blocks that can be found in urban morphologies are selected: the form of individual buildings (Bruse and Fleer, 1998; Santamouris, 2006; Hang et al., 2009), the shape of roofs (Huang et al., 2016), vegetation types (Wania et al., 2012; Baldauf, 2017; Kończak et al., 2021), while complex urban patterns (Hang et al., 2009) are not considered in modelling.

The simulated wind tunnel conditions matched those used by the authors (Gromke and Ruck, 2007; Buccolieri et al., 2011; Jeanjean et al., 2017). The settling velocity of traffic pollutant particles was kept constant, the wind speed was standardised, and the processes of particle resuspension and wet deposition were neglected for the purpose of the simulations. This research presents quantitative analyses of UC, and the possible relations between the effects of detailed street morphology and the corresponding street greenery on street ventilation and pollutant dispersion.

The morphological properties of the building blocks (Table I) include: the H/W ratio of UC (from 0.4 to 1), the asymmetry of UC, height of buildings with upper storey height up to P+3 (from 0 to 10.5 m), the direction of the prevailing wind in relation to the orientation of the street grid (parallel and perpendicular), the typology of the thoroughfare (main road, collector road and local road), the position within the street grid in relation to the building block (inside or outside), the layout of street greenery (the type of tree canopy, shrubs and planting). The choice of spatial building blocks elements, the H/W ratio of UC and the characteristics of street greenery are based on related studies of wind tunnel computer models (Ahmad, Khare and Chaudhry, 2005; Ng and Chau, 2014). The selected morphological criteria represent a scale of a medium dense urban area with a built-up factor between 30 and 35% and a utilisation factor between 1.2 and 1.4.

Table II Street greenery – two-part avenue in relation to the height and width of the street canyon

	section view A-A (y = 45.00m) 12.00.01, $PM_{2.5}$	top view (h = 11.0m) 12.00.01, $PM_{2.5}$	legend $PM_{2.5}$ (μgm^{-3})
H/W 1 – 20/20d			
[12×15 m]			
H/W 0.6 – 20/30d			
[12×15 m]			
H/W 0.4 – 20/45d			
[12×15 m]			

Street typologies correspond to different traffic capacities, emissions and influence the transport of pollutants. The geographical orientation of streets is considered because of its influence on natural ventilation and surface temperatures. The last category provides information on the impact of the surrounding area on each individual street. The trees selected represent any deciduous tree species of 15 metres in height with a dense, circular canopy. The dry biomass weight is 100,00 gm^{-2} and is simulated for the month of June when canopy density is at its highest.

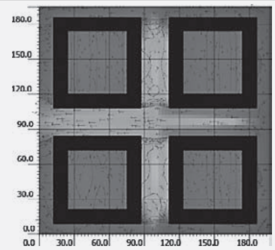
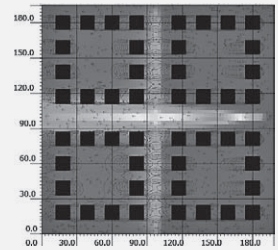
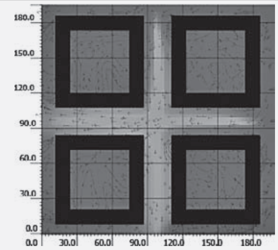
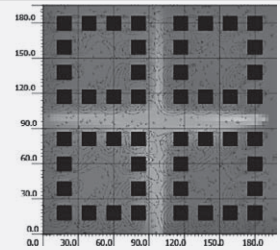
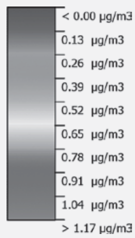
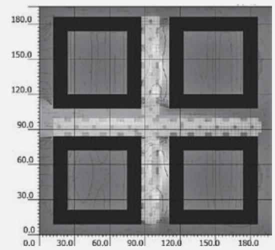
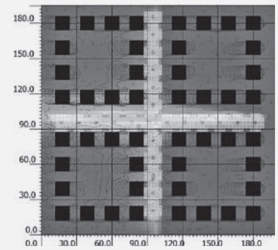
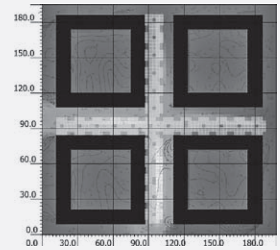
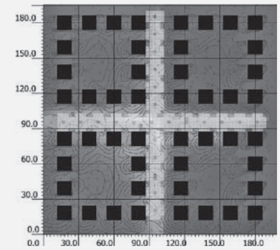
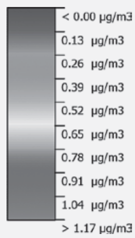
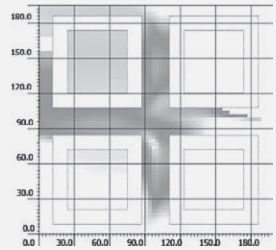
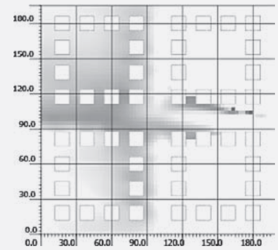
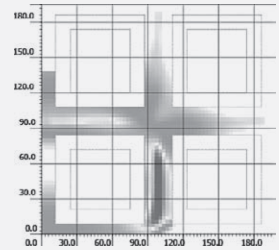
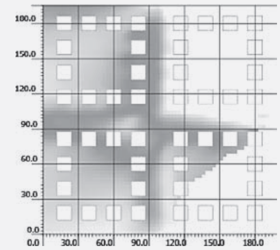
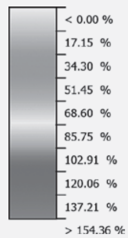
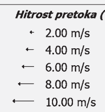
Model Evaluation of Typical Spatial Building Blocks

The data obtained from the analyses are consistent with the findings of other authors in the literature review (Carvalho, Vilhena and Moreira, 2007; Gromke and Ruck, 2007; Abhijith et al., 2017a), and identify different ways and options to influence the transport of pollutants in the open urban space of the street and air quality at the pedestrian level. The built environment, morphology and street greenery have an effect on wind flow patterns, and accelerate or decelerate the transport of particulate pollutants in space. A partial finding suggests that reduced air exchange may be due to the presence of street greenery in the UC, especially at the level below the tree canopy. The implications are not straightforward, as this does not consider the efficiency of particle deposition or the multiplicative effects of the relationship between morphology and vegetation infrastructure on local airflows and turbulence. An individual scheme in space should be considered in terms of its scale and analysed on a case-by-case basis, assessing meteorology, building morphology and vegetation interactions.

In the wind tunnel, the wind speed was constant and in the direction perpendicular to the direction of the street (from left to right), with the exception of a case presented in Table III, where the wind direction is presented in a deflection. The source of $PM_{2.5}$ pollutants is constant in both models on the axis of the thoroughfare in the middle of the street canyon. All situational illustrations are made at a height of 1.5 m or at pedestrian height.

Table II shows the street greenery models, tree canopy types and planting methods. All models are positioned in open space with the same input mass of pollutants of linear origin. All trees are deciduous trees with a spherical canopy. Low trees (5 m), medium trees (15 m) and tall trees (20 m) with a spreading canopy and a linear shrub planting of 2 m are presented. It is evident from the illustration that mature tree plantations stop the movement of particles at pedestrian height (1.5 m) better in the setback than in the case where they are planted close to the source (axis of the thoroughfare). Low trees with a thinner canopy stopped the transport of particles to a lesser extent than trees with a larger canopy, where the difference is 61%. The model with linear shrub planting proved to be the most effective in stopping the trans-

Table III Built environment – Orientation of the street network

	top view A (h=1.50 m) 12.00.01, $PM_{2.5}$ – wind direction 0°	top view B (h=1.50 m) 12.00.01, $PM_{2.5}$ – wind direction 0°	top view A (h=1.50 m) 12.00.01, $PM_{2.5}$ – wind direction 45°	top view B (h=1.50 m) 12.00.01, $PM_{2.5}$ – wind direction 45°	legend $PM_{2.5}$ (μgm^{-3})
u1 – no treeline					
u2– one-sided treeline					
relative difference u1/u2					
	model u1/ A – model u2/ A wind direction 0°	model u1/ B – model u2/ B wind direction 0°	model u1/ A – model u2/ A wind direction 45°	model u1/ B – model u2/ B wind direction 45°	

port of particles further downwind at pedestrian height. The higher pollutant retention rate of shrubs can be explained by their smaller distance from the pollutant source than the distant tree canopy. In a comparable study (Gromke, Jamarkattel and Ruck, 2016), the authors found that in the presence of a continuous hedgerow, the concentration of traffic emissions at the pedestrian level decreases by up to 60%. A 30% decrease in the concentration of particulates can be discerned at a distance of 10 m from the edge of the roadway. It should be noted that in all models the direction of flows is oriented perpendicular to the street array.

The results coincide with the findings of authors (Blocken and Carmeliet, 2004; Morakinyo, Lam and Hao, 2016; Tong et al., 2016; Jeanjean et al., 2017; Santiago, Martilli and Martin, 2017), which found up to 25% increased pollutant concentrations in front of tall shrubs behaving as a solid barrier in space, and reduced concentrations behind the barrier where the wind slowed down and then the effect was no longer detectable, due to reduced particle dispersion. In our model, we observed elevated particle concentrations even 2-3 m behind the vegetation barrier, which can be attributed to the porosity of the shrubs for wind currents, which slows down the dispersion of particles and stops the transport, but not within a negligible distance. We hypothesise that the ability to stop transport and the ability to deposit particulate pollutants on leaf surfaces, depends on the type of vegetation barrier and the density of greenery. At the pedestrian level, an average 7% reduction in traffic emissions was found in the off-street canyon area in Leicester (Buccolieri et al., 2018). In all models considered, it can be observed that at a distance of 20 m from the line source of emissions, pollutant concentrations are reduced by more than 50% downwind. At a downwind distance of 35 m, pollutant concentrations access ambient levels, reaching 50 m.

Table III shows the built environment models used to test the orientation of the street grid, and UC in relation to the prevailing wind direction. Floor plan A represents the street layout of an atrium building block at a height of P+4. Floor plan B represents the street layout of a row of single or semi-detached dwellings at a height of P+2. As shown in model u1/ floor plan A, the street canyon has 50% higher pollutant levels perpendicular to the wind direction. As expected, there is a higher wind speed in the downwind direction along the street and a better dispersion of particulate matter at 1.5 m height.

In the case of model u1/floor plan B of the individual building fabric, the values are reversed, and the particulate concentration is 66% lower, as there is more turbulence in the direction of the street perpendicular to the wind direction, which helps the air exchange with the surroundings. At the same time, less wind flow can be seen along the street with lower flow velocity on the street in the direction of the wind. In the case of a 45° wind direction, the picture is different, with 34% lower maximum concentrations (83-54 μgm^{-3}),

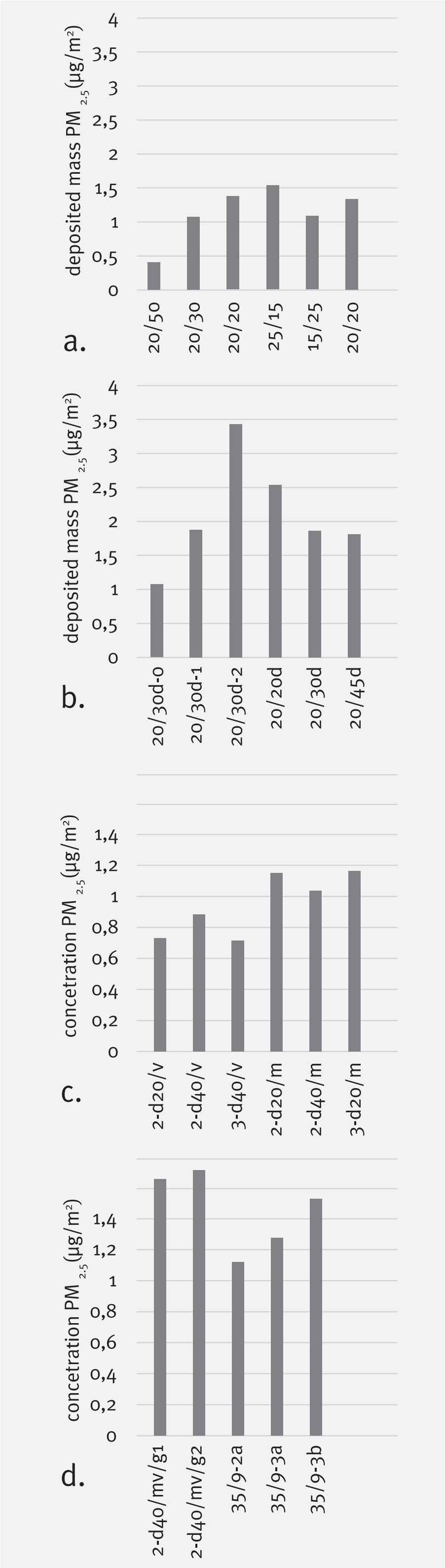


Fig. 1 Results of the built environment and street greenery modelling scenarios: a.-d.

the two variations of the morphology of floor plan A and B are more similar, and the highest concentrations in both floor plans occur at the intersection of the two streets. The results are consistent with the findings of authors (Wania et al., 2012); Garbero, Salizzoni and Soulhac, 2010), who note the important influence of intersections on the ventilation and dispersion of pollutants, where larger eddies and vertical air exchange can occur.

In the model u2 (Table III), where single-unit tree-lined avenues with contiguous canopy is illustrated in both street orientations, the concentrations of pollutants of traffic origin are higher, ranging from 20 to 50%, at a height of 1.5 m. From the figure in the third row, it can be seen that the differences in the model with and without the boardwalk are highest in the case of the atrium block, which forms the street canyon, while the differences on floor plan B are less marked. The difference in pollutant concentrations in the inner atria, the closed and semi-closed atrium cases of floor plan A and B, is smaller, ‹10%. In the case of model u2 with the tree block, the reduced pollutant concentration at 45° offset is less pronounced than in the case of model u1 without the tree block. From the above, it can be concluded that the characteristics of the street morphology, including street width and H/W ratio, side openings and intersections, are closely related to the air flow patterns and pollutant dispersion in UC. Side street openings and intersections have a significant influence on air flows in UC, and the effects are particularly pronounced in the uniform and dense distribution of morphological voids (side street openings). Regardless of the wind direction, the wind conditions inside the atriums of enclosed building blocks are stable. The air quality inside them remains unperturbed in all simulations, which means that traffic pollutants are generally not easily transported into the built environment.

Initial results showed the dependence and magnitude of street greenery and wind barriers on different variables. The most relevant dependent variable is the horizontal pattern of pollutant concentration in the downwind direction, as well as the distance to the maximum concentration and the effectiveness of pollutant dispersion with respect to the individual building blocks in the urban area.

The difference between low and high vegetation in the street canyon can be observed in relation to the street development. High vegetation can be an effective measure in open space where air circulation is not relevant. In open space, low vegetation is more effective in trapping PM pollutants of traffic origin at heights of up to 2 m. In the scenario of a street space with perimeter walls, the ability for advection is limited and consequently the capacity for dispersion of traffic pollutants is reduced. In such an area, high green cover is a negative phenomenon in the context of traffic-derived pollutants at street level when they are of greater concern than the ambient concentration of pollution outside of the UC.

The results of the total deposited $PM_{2.5}$ mass and $PM_{2.5}$ concentrations for the built environment and street greenery modelling scenarios are shown in the figure 1. The results also include the data for spatial configurations not specifically highlighted in the Table II). Thus, point a. of Figure 1 (a.-d.) shows the analyses of three street canyon models without greenery (without tree or shrub planting) in the H/W ratios 20/20, 20/30, 20/50 and 15/25, 25/15 and 20/20. With higher H/W ratios, there is a clear gradual decrease in the total mass deposited. A slightly higher proportion is evident with the asymmetry of the UC in the 25/15 ratio. Point b. shows three different H/W ratios in the UC, which are also presented in the table (Table II), at different distances from the thoroughfare with three planting systems along the thoroughfare. In this case, a higher proportion of the total deposited mass is seen with a higher UC enclosure. All values of the deposited mass for the UC types with a tree canopy are increased. Section c. shows the proportions for UC with different street greenery systems in open space. We find slightly higher total $PM_{2.5}$ concentrations across the model domain for lower canopy tree species. Treetops with higher canopies in open space had less effect than in the narrow street profile of the UK, where they impeded airflow and exchange with the surrounding area. Similarly, in point d., where examples of UC with shrubs are shown, the differences in concentration are smaller. $PM_{2.5}$ concentration fractions were higher for higher hedgerows, and for all models, more effective $PM_{2.5}$ retention is evident for cases with lower green barriers located closer to the source of traffic emissions.

The results of the numerical modelling of the three classes of street tree in the canyon show clear differences in the distribution of $PM_{2.5}$ elements. In the case with the planting of a boardwalk, it can be noted that the windage is lower and thus the effect of particulate retention in the canyon is evident. This effect is greater when the tree canopy is denser, with a larger canopy and trees with dense canopies that block airflow close to the ground. There are minor differences between the cases of different stand spacing and the arrangement of the street greenery building blocks. From the point of view of removing particulate matter from the atmosphere, the system without street greenery is most appropriate in the case of a narrow street canyon. This has a positive effect on the overall concentration and retention of pollutants along the street only at a ratio of 0.5 H/W.

Discussion

Because the vertical air exchange with the surrounding area is crucial for the dispersion and dilution of traffic pollutants at street level, it is necessary to provide fewer barriers, including street greenery, in places where air flow is impeded. The latter is true for street canyons with a narrow profile or a very high H/W ratio, in places with dense peripheral development, or in places where the wind speed is either very weak, or the prevailing direction cannot be measured and a higher degree of turbulence is generated. In these places, the following applies to better dilute traffic pollutants:

– The canopy of trees and shrubs should be permeable or not contiguous, as a too dense canopy diverts flow past it. The total volume of the canopy should not fill the space of the street canyon.

– However, greater spacing between trees ensures better ventilation of the lower parts of the UC, as the eddies created by wind at roof height are better able to penetrate towards the ground.

– Street greenery elements should be located as close as possible to the source of traffic emissions, adjacent to traffic areas, which applies to the location of planting and the height of the canopy volume.

In the scenario of a street space with a medium or low H/W ratio, or in places with less frequent peripheral buildings, it is also possible to accommodate taller street greenery elements that reach or exceed the height of the wreath of the peripheral buildings, the canopy of trees and shrubs may be less permeable, and they may be contiguous. The H/W ratio of the street profile and the ratio of the full empty space in the city is one of the most basic characteristics of the urban morphological image and is closely related to the ventilation of the street and the dispersion of pollutants from traffic sources, as reported by similar studies (Buccolieri et al., 2009; Buccolieri et al., 2018; Gromke and Ruck, 2016). From the analysis of the reference models and through comparison with reference studies, we find that air quality generally improves in a wider open space and with increasing H/W, which means that the vertical air exchange with the environment also increases. In other words, with a wider street profile and at the same time a greater distance from linear sources of traffic pollutants, exposure at street level is relatively lower. The latter is true in cases where traffic pollution is more problematic than ambient levels of air pollutants. Otherwise, pollutants from other sources, such as emissions from industry or heating systems, are more problematic, and the street-level ventilation of the urban fabric itself is of secondary importance.

Model simulations allow us to conclude that urban design, including the morphology and street greenery, is central to the local conditions of wind flow and transport of traffic and other pollutants, and consequently to air quality. The observed differences found in urban environment models support the findings of Aurora Monge-Barrio and others (Monge-Barrio et al., 2022). Building volumes, together with other building blocks in space, as a whole, influence air flows in a way that stops or accelerates them where applicable:

– Buildings perpendicular to the prevailing wind direction moderate the wind speed, while those parallel to the wind direction channel the wind currents and maintain the wind speed to a greater extent.

– Narrow street canyons running transverse to the prevailing wind direction reduce wind speeds and the rate of air exchange from street and roof levels, and larger building setbacks improve ventilation.

– Intersections are places of increased turbulence, vertical air exchange, and in some cases higher levels of traffic pollutants.

– Larger continuous building masses or other built obstructions impede wind flow more than individual buildings.

The local properties of street greenery for air quality therefore requires a site-by-site approach. However, as street greenery elements in the city also have many other positive effects, it is recommended that the guidelines be followed only in cases of existing or projected high traffic pollutant loads in locations where vulnerable populations such as children, the elderly or the sick are also at risk.

The modelling studies considered the aerodynamic effects of built barriers and trees, as well as the effects of pollutant transport under idealised scenarios. Through our assessment of some basic urban planning and landscape-architectural design decisions, we have identified the importance of spatial building blocks on mass-traffic flows, microclimatic conditions and air quality in urban space. More open areas allow for higher levels of air circulation, providing greater opportunities for pollutant removal, which is consistent with the findings of similar studies (Fu et al., 2017; Oke et al., 2017; Vardoulakis et al., 2002). Reduced air circulation capacity leads to a limited ability to disperse pollutants and to exchange air with the surroundings and the upper atmosphere. This may imply a deterioration in scenarios where traffic pollutants represent the most significant air quality burden or where the situation at the level of the thoroughfare is worse than the ambient values in the urban atmosphere.

Conclusion

It can be concluded that the built environment and spatial building blocks have an impact on air quality at street level, and that guidelines for urban design and planning, in terms of ensuring better air quality, can be set. However, it should be underlined that these recommendations are not necessarily applicable in all cases or locations. They depend on local microclimatic conditions and chaotic (turbulent) wind conditions, and consequently the response needs to be tailored to individual cases and configurations. Ideal scenarios thus relate to urban density and street greenery, and it is only reasonable to ensure these spatial relationships when developing new urban areas. For the renewal of urban fabric and degraded urban areas, these guidelines are limited, and the results are theoretical.

Due to the assumptions of the study and the limitations of the computational model, the above conclusions should be applied with caution, carefully checked, and local specificities and priorities considered before the positive effects of the vegetation barrier are realised in the actual space. This is because the pattern of pollutant transport and deposition is a locally dependent variable. The research is limited to simplified models with limited results and accuracy of pollutant dispersion simulations.

In future research, we therefore propose to address more complex spatial patterns with more advanced computational models that address the temporal component of transport, deposition and resuspension processes of transport pollutants.

[Translated by Tjaša Kresnik, LEEMETA, specializirane prevajalske rešitve, d.o.o.]

Acknowledgments

This research was funded by the Slovenian Research Agency (ARRS) through the Young Researchers Programme and the Research Program "Sustainable planning for the quality living space" (P5-0068). This study did not require ethical approval. The authors declare no conflicts of interest.

Bibliography

1. Abhijith, K.V. et al. (2017a) 'Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review', *Atmospheric Environment*, 162, pp. 71-86. Available at: https://doi.org/10.1016/j.atmosenv.2017.05.014.
2. Abhijith, K.V. et al. (2017b) 'Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review', *Atmospheric Environment*, 162, pp. 71-86. Available at: https://doi.org/10.1016/j.atmosenv.2017.05.014.
3. Ahmad, K.; Khare, M. and Chaudhry, K.K. (2005) 'Wind tunnel simulation studies on dispersion at urban street canyons and intersections – A review', *Journal of Wind Engineering and Industrial Aerodynamics*, 93(9), pp. 697-717. Available at: https://doi.org/10.1016/j.jweia.2005.04.002.
4. Bady, M.; Kato, S. and Huang, H. (2008) 'Towards the application of indoor ventilation efficiency indices to evaluate the air quality of urban areas', *Building and Environment*, 43(12), pp. 1991-2004. Available at: https://doi.org/10.1016/j.buildenv.2007.11.013.
5. Baldauf, R. (2017) 'Roadside vegetation design characteristics that can improve local, near-road air quality', *Transportation Research Part D: Transport and Environment*, 52, pp. 354-361. Available at: https://doi.org/10.1016/j.trd.2017.03.013.
6. Blocken, B. and Carmeliet, J. (2004) 'Pedestrian Wind Environment around Buildings: Literature Review and Practical Examples', *Journal of Thermal Envelope and Building Science*, 28(2), pp. 107-159. Available at: https://doi.org/10.1177/1097196304044396.
7. 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), pp. 373-384. Available at: https://doi.org/10.1016/S1364-8152(98)00042-5.
8. Buccolieri, R. et al. (2011) 'Analysis of local scale tree-atmosphere interaction on pollutant concentration in idealised street canyons and application to a real urban junction', *Atmospheric Environment*, 45(9), pp. 1702-1713. Available at: https://doi.org/10.1016/j.atmosenv.2010.12.058.
9. Buccolieri, R.; Gromke, C.; Di Sabatino, S. and Ruck, B. (2009) Aerodynamic effects of trees on pollutant concentration in street canyons. *Science of The Total Environment*, 407(19), pp. 5247-5256. https://doi.org/10.1016/j.scitotenv.2009.06.016
10. Buccolieri, R. et al. (2018) 'The impact of trees on street ventilation, NOx and PM2.5 concentrations across heights in Marylebone Rd street canyon, central London', *Sustainable Cities and Society*, 41, pp. 227-241. Available at: https://doi.org/10.1016/j.scs.2018.05.030.
11. Carvalho, J.C.; Vilhena, M.T. and Moreira, D.M. (2007) 'Comparison between Eulerian and Lagrangian semi-analytical models to simulate the pollutant dispersion in the PBL', *Applied Mathematical Modelling*, 31(1), pp. 120-129. Available at: https://doi.org/10.1016/j.apm.2005.08.009.

12. Chan, T.L. et al. (2002) 'Validation of a two-dimensional pollutant dispersion model in an isolated street canyon', *Atmospheric Environment*, 36(5), pp. 861-872. Available at: https://doi.org/10.1016/S1352-2310(01)00490-3.
13. Chen, X. et al. (2015) 'Efficiency differences of roadside greenbelts with three configurations in removing coarse particles (PM10): A street scale investigation in Wuhan, China', *Urban Forestry & Urban Greening*, 14(2), pp. 354-360. Available at: https://doi.org/10.1016/j.ufug.2015.02.013.
14. Crank, P.J. et al. (2018) 'Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies', *Urban Climate*, 26, pp. 188-197. Available at: https://doi.org/10.1016/j.uclim.2018.09.002.
15. Fu, X.; Liu, J., Ban-Weiss, G.A.; Zhang, J.; Huang, X.; Ouyang, B.; ... & Tao, S. (2017) Effects of canyon geometry on the distribution of traffic-related air pollution in a large urban area: Implications of a multi-canyon air pollution dispersion model. *Atmospheric Environment*, 165. https://doi.org/10.1016/j.atmosenv.2017.06.031
16. Garbero, V.; Salizzoni, P. and Soulhac, L. (2010) 'Experimental Study of Pollutant Dispersion Within a Network of Streets', *Boundary-Layer Meteorology*, 136(3), pp. 457-487. Available at: https://doi.org/10.1007/s10546-010-9511-2.
17. Gromke, C.; Jamarkattel, N. and Ruck, B. (2016) 'Influence of roadside hedgerows on air quality in urban street canyons', *Atmospheric Environment*, 139, pp. 75-86. Available at: https://doi.org/10.1016/j.atmosenv.2016.05.014.
18. Gromke, C. and Ruck, B. (2007) 'Influence of trees on the dispersion of pollutants in an urban street canyon – Experimental investigation of the flow and concentration field', *Atmospheric Environment*, 41(16), pp. 3287-3302. Available at: https://doi.org/10.1016/j.atmosenv.2006.12.043.
19. Hang, J. et al. (2009) 'Pollutant dispersion in idealised city models with different urban morphologies', *Atmospheric Environment*, 43(38), pp. 6011-6025. Available at: https://doi.org/10.1016/j.atmosenv.2009.08.029.
20. Huang, Y.-D. et al. (2016) 'Impacts of shape and height of building roof on airflow and pollutant dispersion inside an isolated street canyon', *Environmental Forensics*, 17(4), pp. 361-379. Available at: https://doi.org/10.1080/15275922.2016.1230912.
21. Jeanjean, A.P.R. et al. (2017) 'Air quality affected by trees in real street canyons: The case of Marylebone neighbourhood in central London', *Urban Forestry & Urban Greening*, 22, pp. 41-53. Available at: https://doi.org/10.1016/j.ufug.2017.01.009.
22. Koblar, S. (2016) 'Prometna obremenjenost cest v Ljubljani', *Urbani izziv* [Preprint].
23. Kończak, B. et al. (2021) 'Assessment of the ability of roadside vegetation to remove particulate matter from the urban air', *Environmental Pollution*, 268, p. 115465. Available at: https://doi.org/10.1016/j.envpol.2020.115465.
24. Kurppa, M. et al. (2018) 'Ventilation and Air Quality in City Blocks Using Large-Eddy Simulation – Urban Planning Perspective', *Atmosphere*, 9(2), p. 65. Available at: https://doi.org/10.3390/atmos9020065.
25. MeshkinKiya, M. & Paolini, R. (2021) 'Uncertainty of solar radiation in urban canyons propagates to indoor thermo-visual comfort'. *Solar Energy*, 221, pp. 545-558.
26. Monge-Barrio, A.; Bes-Rastrollo, M.; Dorregaray-Oyaregui, S.; González-Martínez, P.; Martin-Calvo, N.; López-Hernández, D.; Arriazu-Ramos, A. & Sánchez-Ostiz, A. (2022) Encouraging natural ventilation to improve indoor environmental conditions at schools. Case studies in the north of Spain before and during COVID. Energy and Buildings, 254, 111567. https://doi.org/10.1016/j.enbuild.2021.111567
27. MOP – Ministry of Environment and Spatial Planning, Surveying and Mapping Authority of the Republic of Slovenia. E-Suraying Data. Available online: https://www.gov.si/en/state-authorities/bodies-within-ministries/surveying-and-mapping-authority/ (accessed on 25 April 2020).
28. Morakinyo, T.E.; Lam, Y.F. and Hao, S. (2016) 'Evaluating the role of green infrastructures on near-road pollutant dispersion and removal: Modelling and measurement', *Journal of Environmental Management*, 182, pp. 595-605. Available at: https://doi.org/10.1016/j.jenvman.2016.07.077.
29. Ng, W.-Y. and Chau, C.-K. (2014) 'A modelling investigation of the impact of street and building configurations on personal air pollutant exposure in isolated deep urban canyons', *Science of The Total Environment*, 468-469, pp. 429-448. Available at: https://doi.org/10.1016/j.scitotenv.2013.08.077.
30. Oke, T.R.; Mills, G.; Christen, A. & Voogt, J.A. (2017) Urban Climates. Cambridge University Press. https://doi.org/10.1017/9781139016476
31. Sabatino, S.D. et al. (2008) 'Flow and Pollutant Dispersion in Street Canyons using FLUENT and ADMS-Urban', *Environmental Modelling & Assessment*, 13(3), pp. 369-381. Available at: https://doi.org/10.1007/s10666-007-9106-6.
32. Salmond, J.A. et al. (2013) 'The influence of vegetation on the horizontal and vertical distribution of pollutants in a street canyon', *Science of The Total Environment*, 443, pp. 287-298. Available at: https://doi.org/10.1016/j.scitotenv.2012.10.101.
33. Salmond, J.A.; Tadaki, M.; Vardoulakis, S.; Arbuthnott, K.; Coutts, A.; Demuzere, M.; Dirks, K.N.; Heaviside, C.; Lim, S.; Macintyre, H.; McInnes, R.N. & Wheeler, B.W. (2016) Health and climate related ecosystem services provided by street trees in the urban environment. *Environmental Health*, 15(1), S36. https://doi.org/10.1186/s12940-016-0103-6
34. Santamouris, M. (ed.) (2006) *Environmental design of urban buildings: an integrated approach*. London; Sterling, VA: Earthscan.
35. Santiago, J.-L.; Martilli, A. and Martin, F. (2017) 'On Dry Deposition Modelling of Atmospheric Pollutants on Vegetation at the Microscale: Application to the Impact of Street Vegetation on Air Quality', *Boundary-Layer Meteorology*, 162(3), pp. 451-474. Available at: https://doi.org/10.1007/s10546-016-0210-5.
36. Shen, J. et al. (2017) 'An investigation on the effect of street morphology to ambient air quality using six real-world cases', *Atmospheric Environment*, 164, pp. 85-101. Available at: https://doi.org/10.1016/j.atmosenv.2017.05.047.
37. Tong, Z. et al. (2016) 'Roadside vegetation barrier designs to mitigate near-road air pollution impacts', *Science of The Total Environment*, 541, pp. 920-927. Available at: https://doi.org/10.1016/j.scitotenv.2015.09.067.
38. Vardoulakis, S.; Gonzalez-Flesca, N. and Fisher, B.E.A. (2002) 'Assessment of traffic-related air pollution in two street canyons in Paris: implications for exposure studies', *Atmospheric Environment*, p. 15. https://doi.org/10.1016/S1352-2310(01)00288-6
39. Vos, P.E.J. et al. (2013) 'Improving local air quality in cities: To tree or not to tree?', *Environmental Pollution*, 183, pp. 113-122. Available at: https://doi.org/10.1016/j.envpol.2012.10.021.
40. 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. Available at: https://doi.org/10.1016/j.jenvman.2011.06.036.
41. Zhong, J.; Cai, X.-M. and Bloss, W.J. (2016) 'Coupling dynamics and chemistry in the air pollution modelling of street canyons: A review', *Environmental Pollution*, 214, pp. 690-704. Available at: https://doi.org/10.1016/j.envpol.2016.04.052.

Authors' biographies and contributions

Kristijan Lavtižar, MAU. Currently researching the relationship between space and public health with an emphasis on microclimate conditions, healthy cities and high risk-groups.

Alenka Fikfak, Ph.D., MLA. Scientific and professional interests are focused on rural planning, inclusive design, urban heat islands, healthy cities and urban design.

Janez P. Grom, Ph.D., MLA, Teaching assistant. Research interests include spatial divides and borders in relation to historical conflicts. His current field of work also includes the research of accessibility in urban space and the exploration of architectural and urban heritage.

Conceptualization: K.L., J.G. and A.F.; methodology: K.L.; software: K.L.; validation: K.L., J.G. and A.F.; formal analysis: K.L. and J.G.; investigation: K.L. and J.G.; resources: K.L.; data curation: K.L.; writing – original draft preparation: K.L. and J.G.; writing – review and editing: K.L., J.G. and A.F.; visualization: K.L.; supervision: J.G. and A.F.; project administration: J.G. and A.F.; funding acquisition: K.L. All authors have read and agreed to the published version of the manuscript.