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An ENVI-met Simulation Study on Influence of Urban Vegetation Congestion on Pollution Dispersion

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Abstract: This paper is to assess the impact of the vegetation accumulation on the air pollution dispersion. In order to analyze the idea of the paper for examining the influence of vegetation, two parks in different scales were selected by purpose which are at the same distance from the pollution source. Envi-met (version 3) was selected as research tool based on methodology of the research. Two parks with various scales (local and urban scale) and equal vegetation accumulation were simulated in three cases (status quo or 12%, 37% and 62% vegetation density) and analyzed in quantitative results and graphic images. The results revealed that the extent of area and congestion of vegetation is directly related to decreasing air pollution (CO concentration). Vegetation congestion impact on CO concentration is more impressive for urban scale compared with local scale. The results indicate that decrease of CO concentration in urban scale is going under a regular process. Otherwise, the relationship between vegetation congestion and CO concentration will convert in 62% vegetation congestion. The conclusion of this paper emphasizes that the intensity of vegetation is not always helpful and vegetation might be the cause of intensifying air pollution under certain circumstances.

Key words: Air pollution, vegetation congestion, Envi-met, natural ventilation, depollution of urban spaces.

Introduction

In the 21st century, industrialization and population growth in metropolises are increasing with a remarkable speed. The rate of fuel consumption is ever rising increasingly and it surpasses the medium amount use in other countries (Hoorshenas, 2015). Creating land uses to meet the needs of residents, reducing the share of green spaces in urban fabric, releasing artificial man-made heat from home heating, cars and factories, as well as long wave radiation absorption and reflection have caused many environmental problems. Air pollution is among such consequences and is manifested in the form of the decline of urban air quality. This growing issue in metropolises has affected urban life quality, diseases exposure and sustainability.

Numerous articles assess the relationships of air pollution and human health: The relationship between environmental factors and human health has long been a concern among academic researchers. The paper "The effects of air pollution on human mortality: does gender difference matter in African countries?" used two indicators of environmental pollution, namely particulate matter (PM_{10}) and carbon dioxide (CO_2) to examine the effects of poor air quality on human mortality (Mahdavinejad and Javanroodi, 2016). This study explores an issue that has largely been ignored, particularly in the African literature, where the effect of air pollution on human mortality could be influenced by gender specification. The conclusion of this paper is that the air pollution effects, on average, are similar between genders in the African countries (Normaz Wana and Alhaji Jibrilla, 2016).

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In other paper, “Characterization of particle number concentrations and $PM_{2.5}$ in a school: influence of outdoor air pollution on indoor air”an intensive sampling campaign of indoor and outdoor airborne particulate matter was carried out in a primary school in February 2006 to investigate indoor and outdoor particle number (PN) and mass concentrations ($PM_{2.5}$), and particle size distribution, and to evaluate the influence of outdoor air pollution on the indoor air (Guo et al. 2010). The other study, “Analysis of the association between air pollution and allergic diseases exposure from nearby sources of ambient air pollution within elementary school zones in four Korean cities” assess the relationship between air pollution and allergic disease using the International Study of Asthma and Allergies in Childhood (ISAAC) questionnaire (Kim et al., 2013).

Tehran is one of the most polluted metropolises in the world in which the capacity of refining and absorption of pollutants has decreased. The main reasons for the increase in Tehran`s minimum temperature trend and the formation of heat island are the release of artificial man-made heat from home heating, cars, and factories, as well as absorption or reflection of outgoing long wave radiation by high levels of atmospheric pollutants (Saadatabadi et al., 2006). Aspects such as “amount of public green spaces per inhabitant”, “public parks” and “recreation areas” are often mentioned as important factors to make the city livable, pleasant, and attractive for its citizens (Mahdavinejad and Abedi, 2011).

In order to move towards a more healthy and sustainable city, the use of natural mechanisms as a way of accelerating sustainable urban management can help solve the problem (Mohtashami et al., 2016). One solution proposed in recent studies to reduce the negative environmental effects, which has been considered by urban planners, is green spaces (Alberti et al., 2003; Grimm et al., 2008). Moreover, according to the reports, vegetation has been identified as an effective factor in the promotion of physical activities, mental health and general health of residents (Wania et al., 2012).

Urban green spaces are able to provide a cooler climate through reducing micro urban heat islands. The application of green spaces in urban areas would decrease the ambient temperature between 0.5 and 4°C. Thus, one effective solution, among others, to mitigate urban heat island is the use of vegetation (Qiu et al., 2013). Generally three types of plants are suggested: trees, bushes and grass. Trees have the largest impact on micro ambient climate conditions compared to bushes and grass (Qiu et al., 2013). In general, green spaces play a dual role in the concentration of pollutants and can lead to improved or reduced air quality. This means that on one hand they act as a filter for pollutants, and on the other hand they affect the concentration of some pollutants (Khan and Abbasi. 2001; Wania et al., 2012). Many studies have stressed the important role of vegetation in ventilating and cleaning up the pollutants. The research revealed that plants are more effective in cleaning up pollutants compared to artificial surfaces such as buildings and roads. Buildings as artificial barriers hinder air draft and even at high speed situations, they may cause stagnant and stuffy conditions (Buccolieri et al., 2009; Wania et al., 2012). For example, particle deposition on the leaves of trees has been shown with the help of chemical analyses (Hill, 1971; Bennett et al., 1973).

Investigating the impact of trees on air pollution on a local scale suggests that tree leaves and their presence or absence, the distance of tree from the pollutant source, and wind speed are factors affecting pollution control. The presence or absence of leaves on the tree is another main factor in controlling air pollutants. Trees supply large surfaces such as leaves, stem and skin, which not only reduce wind but also provide an effective surface for removing pollutants (Bealey et al., 2007). The location of the trees is also significant in air pollution control; if trees are close to the pollutant source or where there is a high concentration of pollutants, pollutant control will be strengthened (Beckett et al., 1998; Freer-Smith et al., 2005). Moreover, research showed that nitrogen deposition on vegetation with a short canopy cover depends on the distance from the source of nitrogen, such that with an increase in the distance from the edge of vegetation, the deposition of the pollutants reduces (Verhagen and van Diggelen, 2006). Asman (1998) suggested that deposition of ammonia is less in short vegetation and it will be reduced with an increase in the distance from the pollutant source.

An initial analysis of wind speed showed that at low wind speeds trees have negative effects on the concentration of pollutants, as compared to high wind speed. Air quality is a major concern for citizens (Wania et al., 2012). However, when we consider the concentration of pollutants at pedestrian level, the blockage of wind by plants leads to reduced ventilation and cleaning up of pollutants (Buccolieri et al., 2009). In addition to the above mentioned studies, Litschke and Kuttler (2008) concluded that the particles deposited on the surface of plants are influenced by various factors. Diameter and shape of the particles, planting design, and weather parameters such as relative humidity and wind speed play a major role in air filtering and particle cleanup (Litschke and Kuttler, 2008). In many urban areas, they take advantage of green barriers on the sides of roads in order to limit air and noise pollution and thus preventing such pollutions from reaching the pedestrians; however, their impact on the movement of particles is not fully understood (Al-Dabbous and Kumar, 2014; Mahdavinejad and Fallahtafti, 2015). Although the impact of trees on street ventilation has been explained above, little is known about the effects of trees in dense environments (Wania et al., 2012). Most studies that propose vegetation as a cleaner of air pollutants are based on large scale modelling. Green spaces respond differently on urban scale (McPherson and Simpson, 2003; Jim and Chen, 2008).

In urban environments, planting trees plays a significant role and it also has aesthetic and environmental value. Planting trees as one of the urban characteristics is a major parameter in the quality of urban environments: It controls temperature and removes air pollutants (Buccolieri et al., 2009). Parks with different types of vegetation play a significant role in improving air quality in urban areas. The impact of urban plants on mitigating air pollution has rarely been estimated. Also, the performance of urban parks as urban forests in cleaning up the pollutants has less been studied (Mahdavinejad et al., 2014). Additionally, the effect of climate factors and vegetation conditions in parks on eliminating pollutants is still in question (Yin et al., 2011). In general, plants are known as promoting air quality and thus, improving the life quality of city residents. However, there is little empirical evidence concerning the ability of urban trees in reducing air pollution (Setälä et al., 2013).

Materials and Methods

The ENVI-met Model

This section, in brief, represents the model parameters used to simulate the influence of vegetation congestion on pollution dispersion. We simulated field experiments using ENVI-met V3.1 Beta with typical meteorological conditions to determining the portion of the trees' congestion on CO dispersion by comparing different scenarios in a model area. ENVI-met (Bruse and Fleer, 1998) is a three dimensional computational fluid dynamics (CFD) model that is particularly tailored for simulating different urban atmospheric processes such as pollutant dispersion and microclimate effects (Mahdavinejad et al., 2013). Table 1 summarizes the major input simulation parameters for the ENVI-met.

Table 1: Simulation parameters for the Envi-met software

Typical meteorological day	22/12/2009
Total simulation time (h)	5
Initial atmospheric temperature (K)	283
Wind speed at 10 m above ground level (m/s)	0.8
Wind direction (degree)	210
Roughness length	0.1
Specific humidity (at 2500 m)	4
Relative humidity (in 2 m height).	53.6
Plant	Tree, grass, shrub

In the present study, the density of tree canopy cover, the area they occupy and its impact on air pollution reduction are evaluated. At the same time, the effect of the vastness of the area occupied by vegetation and trees is considered. For the sake of simplicity, the type of vegetation on both sites was considered to be the same.

The focus of this study was on evaluating the relationship between vegetation percentage, the area occupied by it, and the amount of carbon monoxide (CO). Accordingly, two scenarios with two different areas—129000 m^2 and 3200 m^2—were designed. For each scenario, three vegetation densities (12%, 37% and 62%) were defined.

At this point, the determined density of both samples was 12% (in selecting the site, the same density in both samples is one of the main parameters). By inserting meteorological information, we received the CO output. Similarly, both study samples with vegetation densities of 37% and 62% were modelled in ENVI-met and CO output was obtained. Then the outputs were compared in the form of diagrams (we will evaluate them in the Result Part).

Case Study and Experiment

Tehran Air Pollution Characteristics

According to the "City Mayors" website, Tehran, as the sixteenth most populous city in the world, was faced with major problems regarding air quality in 2012. The United States Environmental Protection Agency (USEPA) has selected six major pollutants as indicators and divided them into two groups: primary and secondary. Primary pollutants are substances that are imported directly from the sources of emission into the ambient air and include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), aerosols (PM 10, PM 2.5), and plumbum (Pb). Secondary pollutants refer to substances that are formed due to the interactions in the Earth`s atmosphere, namely ozone (O_3).

As to air pollution in outdoor spaces, primary and basic pollutants turn into secondary pollutants via chemical changes. So, in order to detect such pollutants, their pre-structures must be identified in advance. CO and NO are primary pollutants that are more produced by cars. The peak of such pollutants (CO and NO) differs according to the travel pattern and characteristics and habits of the public.

CO and aerosols are significantly responsible for air pollution in Tehran, as in some hours of the day they reach two times the standard level.

The intended station in this study was a Geophysical Station and its characteristics are shown in Table 2.

Table 2: Characterization of the AQS located in the study domains

AQS location	*Geo-graphical coordinates*	*Height above sea level (m)*	*Distance from nearest roads (m)*	*Distance from nearest building (m)*
Geophysics	35 44′ E 51 23′ N	1419	100	50

The Proposed Scenarios

The two selected parks, namely Roftegar and Goftogou Parks, were selected on local and urban scales, respectively, for field studies. Case studies herein are located in district 2 of Tehran Municipality.

Thus, two parks with various scales (local and urban scale) and equal vegetation accumulation were simulated in three cases: status quo or 12%, 37% and 62% vegetation density (Figures 2 and 3). Moreover, Table 3 shows the general description of the computational domains for both case studies.

The main criteria for the selection of the field experiments were:

(a) The presence of similar tree congestion in both sites. Both Roftegar and Goftogou Parks are covered with vegetation and trees by a density of 12%.

(b) A significant road traffic flux. Both parks are surrounded by Chamran Highway and residential area; no industrial use is located around them and their traffic and environmental conditions are alike.

(c) The existence of an air quality station (AQS) inside the study area. Weather station is the same in both sites.

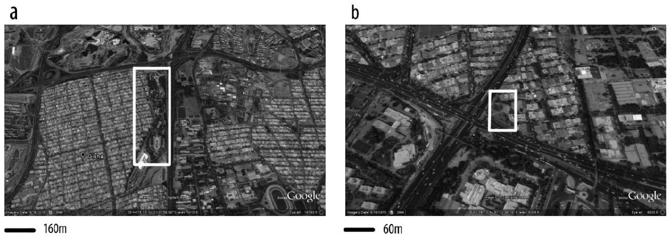

Figure 1: Satellite images of the Goftogou Park (a) and Roftegar Park (b) study areas. The boundaries of the computational domains are shown by the white rectangle.

Table 3: General description of the computational domains (L and W represent, respectively, are the total length and width of the domain, including the open belt around the built area)

Case study	*Domain area L×W (m×m)*	*Buildings height range (m)*	*Trees*	
			Min crown height (m)	*Max height (m)*
Roftegar	45×83	3-18	1.5	3
Goftogou	150×900	6-20	1.5	3

Results

We chose 10:00 am to 17:00 pm because the traffic peak occurs between 10:00 am and 17:00 pm. Modelling results indicate various relationships between the percent tree canopy cover and near ground CO concentration.

Cleanliness Benefit of Trees at the Urban and Local Scale

The increase of the tree canopy cover resulted in a reduction in CO concentration at both urban and local scale. Trees provide more cleanliness effect at the urban scale than the local scale. Figures 4 to 6 show the 8-hour CO concentration in the two sites in terms of their scales.

12 Percent Canopy Covering

There is a relatively large variation in the volume of CO based on Figure 4. The largest occurs at 2 pm, where the maximum amount of CO is over 350.5 ppm, and 349.5 ppm for local and urban scale, respectively. Moreover, the CO difference between the two scenarios reaches a maximum of 1 ppm. It is worth to note that since nearly 4.30 pm, the amount of CO in the local scenario (Goftogou Park) exceeded the urban one, indicating that from this time we witnessed a reverse trend.

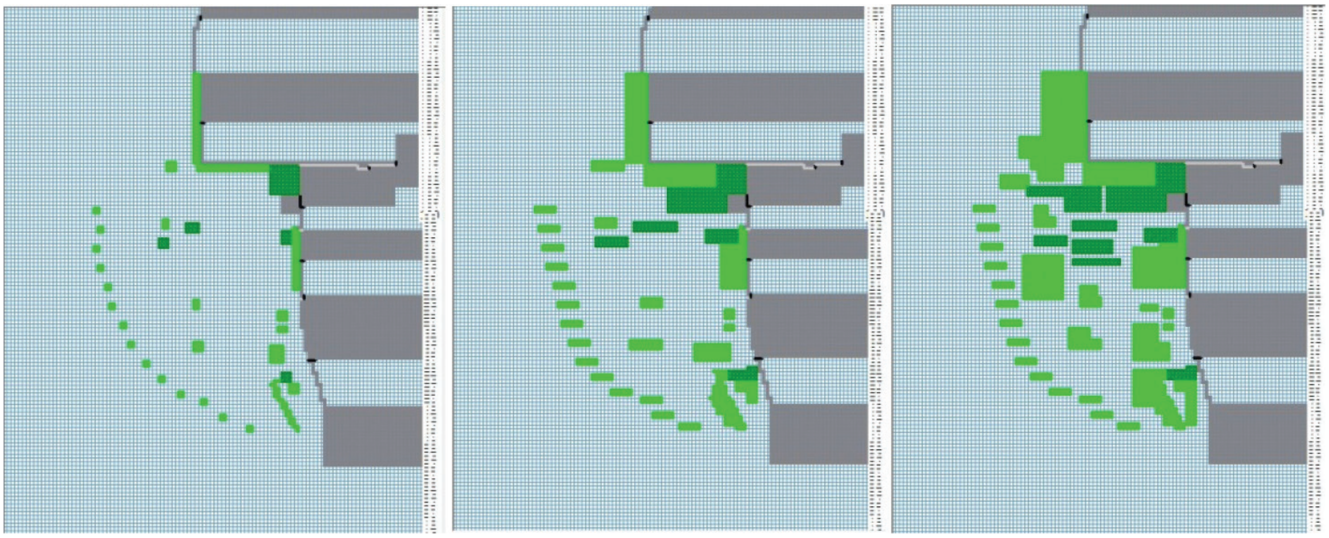

Figure 2: Computational domain generated by Envi-met for Roftegar Park (from right to left: 12%, 37% and 62% vegetation density).

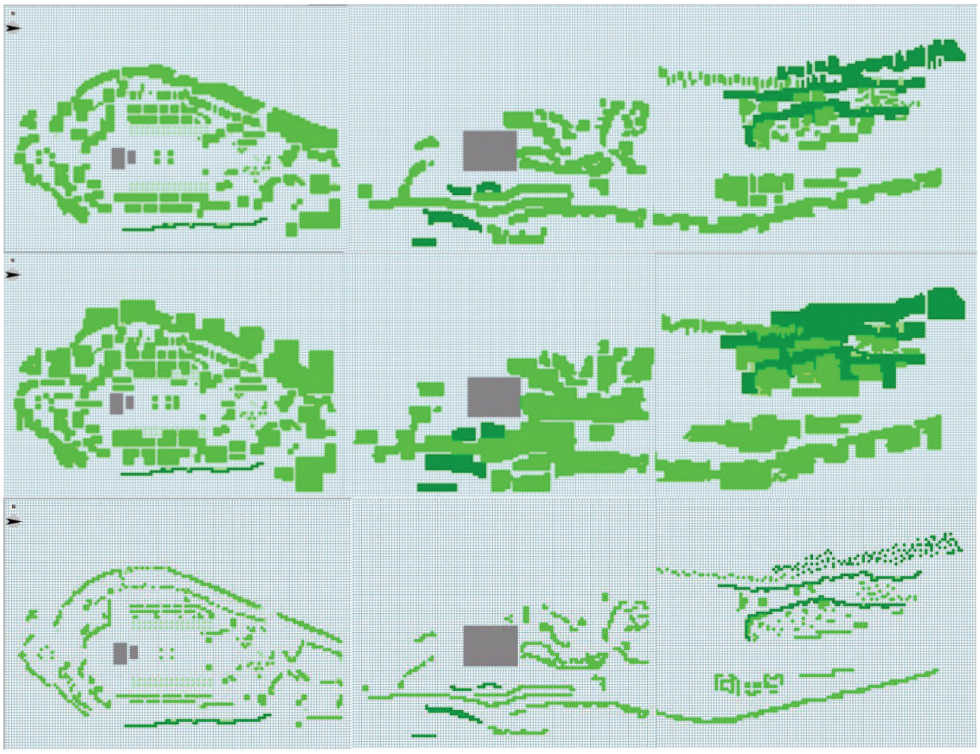

Figure 3: Computational domain generated by Envi-met for Goftogou Park (from up to down: 12%, 37% and 62% vegetation density).

37 Percent Canopy Covering

37 percent canopy covering is largely similar to that of 12 percent, except for urban park (Goftegoo) between 1-2 pm. As the percentage of canopy rose from 12 to 37, the CO concentration saw a marginal decline between 0.5 and 1 ppm. The results clearly show that at 10 am the figure for Roftegar Park stood at well under 348.5 ppm, while that of Goftegoo Park was slightly lower at approximately 347.5 ppm. Over the next three hours, the amount of CO for both scenarios rose by more than 1 ppm, after which they experienced a significant dip to just over 347 ppm at 5 pm, where in both sites the CO concentration reached its lowest during the simulation time.

62 Percent Canopy Covering

In the last simulation, where the locations were covered by 62 percent vegetation, the CO concentration trend was completely different from the two other ones. Figure 6 illustrates that although the total amount of CO decreased, the difference between the two scenarios widened substantially so that in Roftegar Park, far more CO was concentrated than Goftegoo Park. The maximum CO occurs on mid-noon at 2 pm, where the figure for local option was nearly 3 ppm larger than the urban one. The amount of CO for the former is just below 352 ppm and that of latter is 348 ppm. As we can see from the graph, the lowest amount of this pollution index is at the beginning and ending of the simulation interval at approximately 347 and 349 ppm for Goftegoo Park and Roftegar Park, respectively. The noticeable point is that in spite of the last two scenarios, where the CO volume was equal for the two scales at 5 pm, the pollution caused by CO in the smaller alternative is more than the larger site during the whole simulation.

Comparing CO concentration for each scenario separately, we found some significant results. In local scale (Roftegar Park), the relationship between vegetation congestion and CO concentration convert in a turning point (62% vegetation congestion) and make the air more polluted than when it covers by just 37 percent trees. First interval of congestion increasing (12% to 37%) results in a 0.08% decrease of CO concentration, otherwise, a 37% to 62% increase in vegetation results in a 0.2% increase of CO concentration (Figure 8).

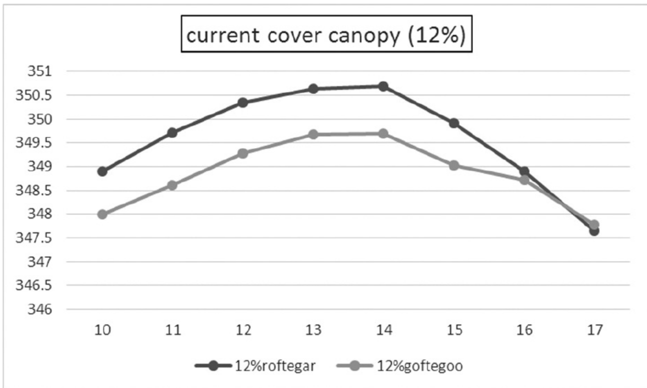

Figure 4: CO concentration, Roftegar and Goftogou Parks, 12% cover canopy.

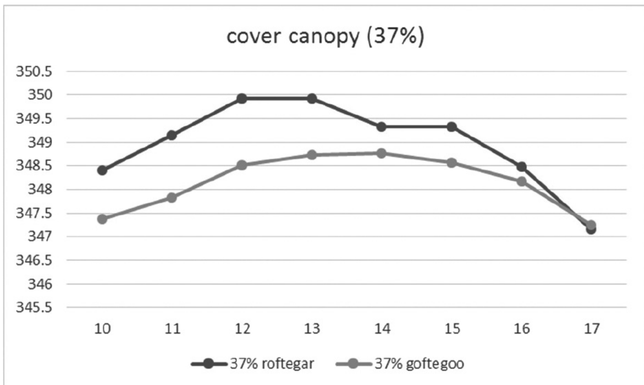

Figure 5: CO concentration, Roftegar and Goftogou Parks, 37% cover canopy.

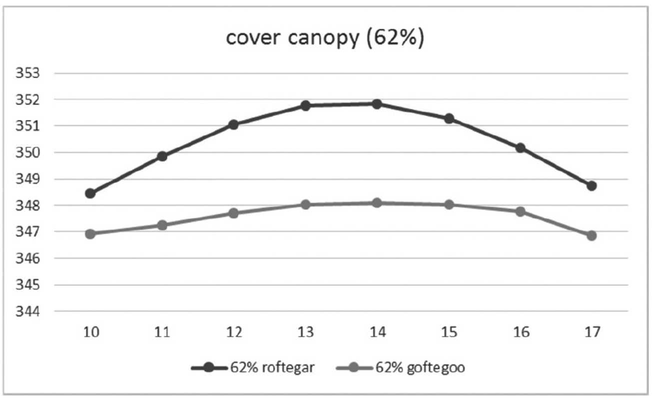

Figure 6: CO concentration, Roftegar and Goftogou Parks, 62% cover canopy.

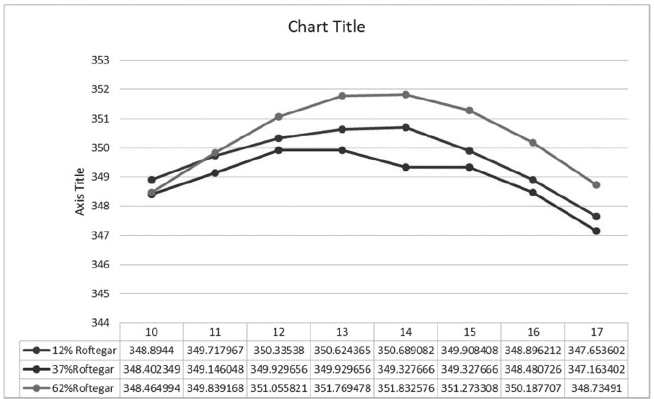

Figure 7: CO concentration, Roftegar Park, different canopy cover.

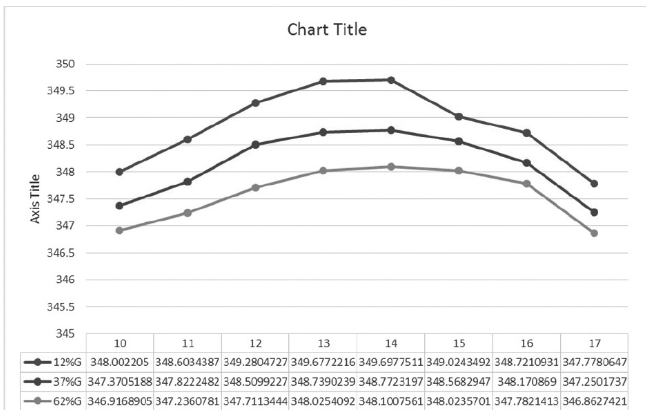

Figure 8: CO concentration, Goftogou Park, different canopy cover.

However, the vegetation congestion impact on CO concentration decreasing in urban scale (Goftegoo Park) is going as a regular process. Based on Figure 10, 25% increase in vegetation congestion (12% to 37%) causes a 0.1% decrease in CO concentration and an increase from 37% to 62% congestion causes a 0.08% decrease in CO concentration.

The concluding remarks, during the experimental time period, are the following:

- In general, in the urban scale, the CO concentration was less than the local park. This result is more impressive for urban scale (Goftogou Park) compared to local scale (Roftegar Park) when air pollution source is close to the site.
- With the increase in the percentage of vegetation, the air quality improved in the urban scale, while it was worse for the local scale when it comes to 62 percent canopy.
- From the above graphs, it becomes obvious that in the first four hours of the simulation up to 2 pm, the air quality declined followed by an improvement in the subsequent hours so that at 5 pm it reached at the lowest amount of CO during the simulated interval.

Conclusions

Due to the devastating impact of air pollution on human health, this environmental issue has become a disturbing problem in metropolises like Tehran. Because of population density and traffic in Tehran, we are increasingly witnessing air pollution concentration in this metropolis as compared to its surrounding areas. Most studies that suggest vegetation as a cleaner of air pollutants are based on large scale modelling (McPherson and Simpson, 2003; Jim and Chen, 2008). Planting trees as one of the urban characteristics is a major parameter in the quality of urban environments: It controls temperature and removes air pollutants (Buccolieri et al., 2009). Regarding the results of the present study, the extent of area (scale) with constant vegetation congestion is a crucial factor in decreasing CO concentration. The extent of area and congestion of vegetation is directly related to decreasing air pollution (CO concentration). Hence, although, trees and vegetation can have a positive impact on air pollution in urban scale, this relation can impose acute problem in smaller scale. The reason why it happens is because the high density of trees and vegetation in local scales will trap air pollution (decrease of air flow in local scale leads to trapping of air pollution). As a result, utilizing tree congestion as a way to alleviate the pollution requires precise evaluation for each and every specific site.

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