

# Quantifying the Effect of Green Urban Spaces as Sinks for Air Pollutants in Lahore, Pakistan

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**Abstract** Vegetation as a sink of air pollutants is well known and models have been developed to describe the processes involved. Vegetation as a sink for air pollutants in one of the most polluted cities in the world, Lahore, Pakistan, has not yet been documented. Lahore is known as the ‘Garden City’ and a model was developed to estimate the role of green urban spaces (GUS) as a sink for air pollutants in the city. Several GUSs in Lahore were described, and tree and leaf area (LA) dimensions were measured. This information formed the vegetation input of the model. The deposition fluxes of the gaseous pollutants and the dry and wet deposition of particulate matter were calculated and then applied to the LA of the GUSs. The precipitated and absorbed quantities of pollutants were contrasted with the amount present in the atmosphere. It was found that even relatively small GUSs have a significant ability to reduce the atmospheric pollutant concentrations. However, when extrapolating these findings to the urban area of Lahore at large, this impact reduces significantly due to the lack of GUSs in Lahore. The pollution generated by the city of Lahore far exceeds what the existing vegetation can accommodate. The existing vegetation of the city therefore needs to be protected, and the area of GUSs increased because without such spaces the city is even worse off. The prevailing atmospheric conditions during the winter months does however, limit the effectiveness of the role of vegetation as a sink for air pollutants.

**Keywords:** Green urban spaces, semi-arid area, pollutant absorption, pollutant deposition

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## 1. Introduction

Air pollution in Lahore, Pakistan, is among the worst in the world. The city features consistently in the top ten most polluted cities according to IQAir [1]. However, the city also has the reputation of being the “garden city” [2]. This is based on the perception that the city has many parks and gardens. By world standards, though, the amount of green open space in the city falls well short of the world standard for sustainable urban ecosystems [3]. At the same time it is also urbanising at a rapid rate with a population growth rate of 4 % and an area growth rate of 7 % [4].

The benefits of green urban spaces (GUS) are well recognised as discussed extensively by [5,6], and particularly with respect to air pollution removal [7,8,9,10]. Despite the role GUS play in the removal of air pollutants, little information is available as to how this would apply to Lahore, particularly given the intensity of air pollution in the city. Several authors have looked at the resilience of urban vegetation in Lahore in the presence of high levels of pollution [11,12]. Reference [13] looked the localised effect of some tree species on the improvement of the particulate matter smaller than 2.5  $\mu\text{m}$  ( $\text{PM}_{2.5}$ ) on an ad-hock basis but did not extend it to larger areas of the

city and other pollutants.

Reference [14] described several approaches to assess the potential of phytoremediation of outdoor air pollutants which consisted of extensive and very detailed plant physiological observations addressing the absorption of gases. Other observations consisted of extensive outdoor observations of dust collections on urban trees. One approach not covered explicitly by [14] is a modelling approach covering the gaseous absorption and dry and wet deposition. This approach can quantify the effect of GUS on air pollution by estimating the level pollutant removal by GUS. One such model is the iTree model from USDA Forest Service “a state-of-the-art, peer-reviewed software suite from the USDA Forest Service that provides urban and rural forestry analysis and benefits assessment tools. The i-Tree tools can help strengthen forest management and advocacy efforts by quantifying forest structure and the environmental benefits that trees provide.” [15]. The model requires input in the form of vegetation and landscape parameters. However, applying this model to Lahore requires verified and formatted datasets for air pollution as well as meteorology, and those data sets are not available for Lahore in the current version of the model. Also user generated inputs are very limited for the iTree model.

The basis for the iTree model is the UFORE (Urban

Forrest Effects) model developed by [16] which is supported by extensive descriptions of model processes and a data collection manual [17]. This model consists of five sub-models of which two were deemed relevant to apply to the situation in Lahore. These are:

**UFORE-A:** A model describing the anatomy of the urban forest which quantifies urban forest structure (e.g., species composition, tree density, tree health, leaf area, leaf and tree biomass) based on field data.

**UFORE-D:** Modelling dry deposition of air pollution quantifying the hourly amount of pollution removed by the urban forest and associated percent improvement in air quality over time. Pollution removal is calculated for ozone ( $O_3$ ), sulphur dioxide ( $SO_2$ ), nitrogen dioxide ( $NO_2$ ), carbon monoxide (CO),  $PM_{2.5}$  and particulate matter smaller than  $10 \mu m$  ( $PM_{10}$ ) based on field, pollution concentration, and meteorological data.

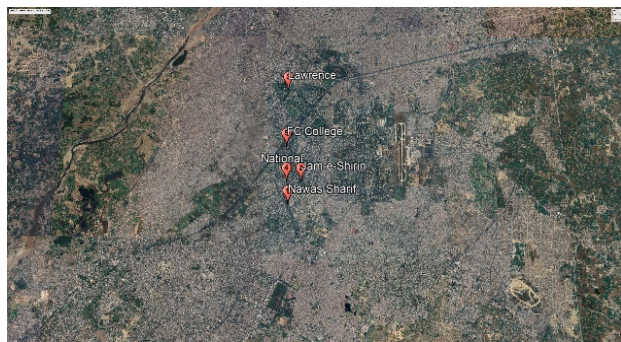
These two sub-models have been well documented and are also described by [18,19] and further in the iTree guide [15]. The descriptions in the respective references provided enough detail to develop a few Excel® spreadsheets to calculate tree parameters and, more importantly, the fluxes driving the absorbance and the dry and wet depositions of air pollutants by the vegetation. These spreadsheets were used to simulate the effect of GUS on the remediation of air pollution in Lahore, Pakistan, for a 2 year period. For that period, extensive air pollution data was available and during that period vegetation estimates of several park areas were obtained.

From this work, the size of the sink of GUS for common air pollutants in one of the most polluted cities of the world was estimated. This paper describes the GUS, the spreadsheet models and the results of the remediation modelling in the context of ambient air pollution levels in Lahore.

## 2. Material and Methods

### GUS descriptions

Four parks (Nawas Sharif (1), Jam-e-Shirin (2), Lawrence (3) and National Park (4)) and one part of the campus of FC College (5) in Lahore, Pakistan were selected for the assessment of the vegetation. The location of those areas is presented in Figure 1.



**Figure 1.** Locations of the 5 GUSs in Lahore, Pakistan. 1 = Nawas Sharif park, 2 = Jam-e-Shirin park, 3 = Lawrence Park, 4 = National Park and 5 = part of the campus of FC College

The effort was focussed on areas where there was a large selection of trees, and sizeable shrubs. The size of

the areas was: 2.91, 2.41, 4.24, 0.89 and 13.0 ha respectively. In each of the areas the number of trees was counted, the height of a sample of similar sized trees was determined by taking a digital photograph with a reference mark a known height attached to the tree. From these photos the tree diameter at breast height (DBH) or at a height of 1.35 m [17], the tree height and the crown dimensions (height and width) were determined using the number of pixels and the scale factor (pixels/cm). This was derived from the height of the reference mark in the photograph as the number of pixels and its real height in centimetres. By looking up through the canopy a rough estimate of the intercepted light as a fraction ( $S$ ) was also determined. For example, if the sky could not be seen  $S = 0.95$ , and when about 50% of the view was occupied by the visible sky,  $S$  was 0.5.

The crown light exposure (i.e. number of sides of each tree receiving light from above) (CLE) was determined.

In the campus area more detailed measurements of the trees were carried out. This consisted of cutting several branches from certain trees and determining the volume of the branches (estimated length x width x height), the number of leaves and the size of the leaves. For the size, the leaves were divided into several groups based on size. For each group, a typical leaf area was determined by taking photos of those leaves, and then determining the area of those leaves using ImageJ® software. The total leaf area from the branch was determined by multiplying the area of the respective leaves by the number of the leaves in each group. After the volume of the tree canopy was estimated from its shape, the total leaf area of the tree was determined by multiplying the leaf area of the branch with the ratio of the total estimated tree canopy volume and the volume of the branches. This approach provided us with a rough comparison between estimating leaf area (LA) of the whole tree using established equations [17] and what was actually present. Reference [20] used a high-lift truck and cutting out a fixed volume of the tree canopy to establish the LA equations. We used individual branches.

An estimate of the total area of GUS in Lahore as a fraction of the total urban area of Lahore was done using Google Earth (GE) and ImageJ®. First, the urban area of Lahore was estimated from GE which was assumed to be bordered by the following well-known features in Lahore: the river Ravi, the Hudiara drain, Barki Road and the Ring Road. The high-resolution image of the area from GE was exported and had a resolution of  $43m^2$  per pixel. In ImageJ® the GE image was imported, and the colours separated into a red, green and blue image. The red image was used to estimate the GUS. Using the threshold and the binary option, the GUS were made black, and then with the particle analysis option of ImageJ®, the size of all the black area was calculated. By altering the threshold, the size of the areas changed but by using known vegetated areas in Lahore as a reference, a realistic representation of the GUS areas could be determined. A range for the GUS, indicated by GUS1 and GUS2 was used. Only areas larger than 0.1 ha were counted in this process.

### Ambient air quality monitoring

The ambient air quality at Forman Christian College (FCC), Lahore (Lat:31.5206 and Long: 74.3368) has been monitored now for several years. The system employed is a Haz-Scanner system from Environmental Device

Corporation (EDC), USA. It is located on the campus of FCC in the residential area of the campus, about 500 m from major arterial roads. The air pollution parameters monitored were particulate matter with a particle size of < 2.5  $\mu\text{m}$  ( $\text{PM}_{2.5}$ ), and particulate matter with a particle size of < 10  $\mu\text{m}$  ( $\text{PM}_{10}$ ) using 90° infra-red (IR) light scattering systems. For carbon dioxide ( $\text{CO}_2$ ), CO,  $\text{NO}_2$ ,  $\text{SO}_2$ ,  $\text{O}_3$  Alpha Sense® sensors were used, while for the temperature and the relative humidity (RH) an HTM2500LF sensor was used. Wind speed and direction and rainfall were obtained with standard EDC equipment. The data was recorded every ten minutes. For the gaseous absorption and the dry deposition of the  $\text{PM}_{2.5}$  and the  $\text{PM}_{10}$ , hourly averages were used, while for the wet deposition daily averages were used. The system has been serviced and calibrated every year by the manufacturer according to USEPA standards.

### Period of interest

The period for the study was determined by the availability of air pollution data which started in early September 2022 until the end of June 2023, then again from the beginning of October 2023 until the beginning of June 2024. This period covered the autumn (Oct – Nov), winter (Dec - Feb) and spring (March – May) periods, typically periods of the worst air pollution. During the summers the pollution is greatly reduced, and air pollution data collected by the EDC Haz-Scanner system was not available for that period.

## 3. Model Description

### GUS

A proper and accurate description of the GUS is very important when the model is used to estimate the potential of the GUS to function as an air pollutant sink. Every tree in the designated area of the GUS was located, counted, described and measured. The description of the general area (the park-scape) was based on tree cover percentage, land use, percentage of ground cover in the park-scape described by areas covered by building, bitumen, other types of pavements, bare soil, scrubs, grass and water.

For each of the trees in the GUS the following parameters are required: DBH, amount of light intercepted (S), height and the width of the crown and CLE.

In the processes involved in the removal of air pollutants by vegetation, the leaf area (LA) is very important and/or the total dry-weight leaf biomass (TDLB). Reference [20,21] developed and presented many regression equations for deciduous species of America [20], and other more diverse regions [21]. Very good correlations were found by them between DBH, TDLB and LA. When based on DBH the equations took the form of equation 1:

$$\ln Y = b_0 + b_1 X + b_2 S \quad (1)$$

And when based on crown parameters, the form of equation 2:

$$\ln Y = b_0 + b_1 H + b_2 D + b_3 S + b_4 C \quad (2)$$

Where  $Y = \text{LA}$  ( $\text{m}^2$ ) or TDLB (g),  $X = \text{DBH}$  (cm),  $S$  the shading factor (fraction light intercepted by foliated tree

crowns),  $H =$  crown height (m),  $D =$  average crown diameter (m) and  $C =$  the outer surface of the tree crown ( $\pi D(H + D)/2$ ). Reference [20] published a list of the constants in the two equations for a great number of trees. The assumption here is that the constants derived for trees in USA, can also be applied to describe the trees in the GUS of Lahore.

Overlapping crowns affected the LA and can be accommodated through the crown light exposure CLE values which range from 0 to 5 [20]. In practice most trees were in the category 4 and 5, hence no further distinction was made in the CLE.

The LA was a significant input variable for the flux model. LA was considered constant for the period under consideration and for a given place hence it was a single constant input, reflecting the entire LA of the GUS in the flux model.

### Flux model

The model is similar in approach as the iTree model as described in detail [16]. The equations describing the process of diffusion and precipitations are presented and discussed by [16]. This sub-model, analogous to the UFORE-D model by [16] describes the absorption of several gaseous air pollutants ( $\text{SO}_2$ ,  $\text{NO}_2$  and  $\text{O}_3$ ) by the leaves as well as the dry and wet deposition processes of the  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ .

The dry deposition is described as the flux ( $F$ ,  $\text{g.m}^{-2}.\text{s}^{-1}$ ) which is the product of the concentration of the pollutants in the air ( $C$ , in  $\text{g.m}^{-3}$ ) and the deposition velocity  $V_d$  in  $\text{m.s}^{-1}$ .

$$F = V_d \times C \quad (3)$$

The deposition velocity is the inverse sum of the aerodynamic resistance ( $R_a$ ) and the quasi-laminar boundary layer ( $R_b$ ) and the canopy ( $R_c$ ) resistances [22] (Eq. 4):

$$V_d = \frac{1}{R_a + R_b + R_c} \quad (4)$$

### Aerodynamic resistance

The aerodynamic resistance ( $R_a$ ) was calculated as described by [16] (Eq. 5):

$$R_a = u(z) \times u^{*-2} \quad (5)$$

where  $u(z)$  is the wind speed ( $\text{m.s}^{-1}$ ) at a height ( $z$ , in m) while the  $u^*$  is the friction velocity ( $\text{m.s}^{-1}$ ). This friction velocity ( $u^*$ ) is governed by, among other things, the stability of the atmosphere at a given time.

The stability of the atmosphere is determined by the vertical profile of the air temperature, or the lapse rate (LR) compared to the adiabatic lapse rate (ALR) of the temperature [23].

Three different conditions are considered for atmospheric stabilities:

- Unstable: This typically occurs during daytime, when the land surface is heated by incoming solar radiation which in turn heats up the air above it. This creates vertical motion, and the heat flux is directed upward.
- Stable: This typically occurs typically during the night, when outgoing radiation dominates, air is

cooled from below and air density increases closer to the ground. This condition limits the vertical motion of air and heat flux is directed downward.

- Neutral: This condition is somewhere between the stable and the unstable conditions, considered to occur around sunset or sun-down or under heavy clouding and/or strong winds. In this condition the vertical motions of air are not affected significantly, and heat flux is zero.

The friction velocity ( $u^*$ ) is calculated as follows (Eq. 6):

$$u^* = (k \times (u(z-d)) [\ln \ln ((z-d) \times z_0 - 1) - \psi M ((z-d) \times L - 1) + \psi M (z_0 \times L - 1)]) \quad (6)$$

where  $k$  = von Karman constant (0.4),  $d$  = displacement height (m),  $z_0$  = roughness length (m),  $\psi M$  = stability for momentum and  $L$  = the Monin-Obukhov (MO) stability length.

The MO stability length ( $L$ ) can be estimated in many ways, some rather complex, others more straight forward. Simply stated the MO length reflects the height at which turbulence is generated more by buoyancy of the air than by wind shear. By definition  $L$  is usually negative in the daytime and at night  $L$  becomes positive while at dawn and at dusk  $L$  passes through zero [24].

Other atmospheric stability classes such as the Pasquill stability classes are more common and can be determined according to [25]. The various Pasquill classes can be related to MO stability length according to [26]. While a range of MO lengths is given, in the calculations the  $L_{\text{mean}}$  was used.

For the unstable condition ( $L < 0$ ) the  $\psi M$  (stability for momentum) is calculated using Eq. 7.

$$\psi M = 2 \ln [0.5(1+X)] + \ln [0.5(1+X^2)] - 2 \tan^{-1}(X) + 0.5\pi \quad (7)$$

Where  $X = (1 - 28 z L^{-1})^{0.25}$

For stable conditions ( $L > 0$ ) the friction velocity is calculated using Eq. 8.

$$u^* = C_{DN} u \left\{ 0.5 + 0.5 \left[ 1 - \ln \left[ 0.5 + 0.5 \left[ 0.5 \left( 1 - 2u_o / \left( C_{DN}^2 \times u \right) \right)^2 \right] \right] \right]^{1/2} \right\} \quad (8)$$

where  $C_{DN} = k (\ln (z/z_0))^{-1}$ ;  $u_o^2 = (4.7 \text{ a g } \theta) T^{-1}$ ;  $g = 9.81 \text{ m.s}^{-2}$ ;  $\theta = 0.09 (1 - 0.5 N^2)$ ;  $T$  = air temperature ( $K^\circ$ ); and  $N$  = fraction of opaque cloud cover [27].

So the determination of the stability classes depends on the wind speed, the solar radiation, and the time of day (day time, dawn/dusk or night time). In the model, the time of sunrise and sunset was determined for Lahore for a given day [28] which according to [26] attracts a stability class of D. Then, according to wind speed and solar radiation the Pasquill classes were allocated for every hour and the associated MO stability length.

#### Quasi-laminar boundary layer resistance

The quasi-laminar boundary layer resistance ( $R_b$ ) describes the resistance to the flow of vapour or heat. This laminar boundary-layer flow occurs when a moving fluid, like air, comes in contact with a solid surface and it has a

resistance to vapour flow. This resistance ( $R_b$ ) is calculated using Eq.9.

$$R_b = 2S_c^3 \text{Pr}^{-\frac{2}{3}} (k \times u^*)^{-1} \quad (9)$$

Where  $k$  = von Karman constant (0.4),  $S_c$  = Schmidt number (0.2 – 6, usually 1), and  $\text{Pr}$  = the Prantl number (0.7 – 0.9, usually 0.85)[29].

#### Canopy resistances

Once the gases, such as  $\text{SO}_2$ ,  $\text{NO}_2$ , and  $\text{O}_3$  arrive at the tree canopy or the leaf surface they need to overcome the canopy resistance ( $R_c$ ) to enter the leaves. These resistances were modelled as described by [22]. The canopy resistance has three components: the stomatal resistance ( $r_s$ ), mesophyll resistance ( $r_m$ ) and then the cuticular resistance ( $r_t$ ) such that (Eq. 10)

$$\frac{1}{R_c} = \frac{1}{(r_s + r_m)} + \frac{1}{r_t} \quad (10)$$

The  $r_m$  for the various gases was presented by Novak (2020) with the following values: 0, 10 and 100  $\text{s.m}^{-1}$  for  $\text{SO}_2$ ,  $\text{O}_3$  and  $\text{NO}_2$  respectively. The  $r_t$  for  $\text{SO}_2$ ,  $\text{O}_3$  and  $\text{NO}_2$  was 8,000, 10,000 and 20,000  $\text{s.m}^{-1}$  respectively.

The calculation of the stomatal resistance ( $r_s$ ) was significantly more involved, as presented by [22]. The  $r_s$  is dependent on the air temperature, the wind speed, the photosynthetically active radiation (PAR), the leaf area (LA), the vapour deficit, the level of water stress as well as the ratio of molecular diffusivity of the respective gases  $\text{SO}_2$ ,  $\text{O}_3$  and  $\text{NO}_2$  and water. Because the air temperature, the wind speed and PAR varies during the day, the  $r_s$  varies accordingly over time. The PAR was obtained from [30].

Once the  $R_c$  was calculated it was combined with  $R_a$  and  $R_b$  to calculate the  $V_d$  using eq. 7. The  $V_d (\text{m.s}^{-1})$  was then multiplied by the actual concentration ( $\text{g.m}^{-3}$ ) of the respective pollutants to determine the flux ( $F$ ) ( $\text{g.m}^{-2}.\text{s}^{-1}$ ) using equation 6.

#### Dry deposition of PM

The dry deposition  $V_d$  of PM was determined from average values obtained from the literature [31,32,33], for  $\text{PM}_{10}$ ,  $V_d = 0.032 \text{ m.s}^{-1}$  and for  $\text{PM}_{2.5}$ ,  $V_d = 0.0032 \text{ m.s}^{-1}$ . The  $V_d$  was then multiplied by the concentration to give the flux ( $\text{g.m}^{-2}.\text{s}^{-1}$ ), which was then multiplied with a certain time period (day, month, year) to give the total mass of the PM removed through dry deposition per day, month or year.

#### Wet deposition of particulate matter

The wet deposition of the PM is associated with the rainfall, and rainfall intensity which result in a scavenging efficiency (SE) [34]. Reference [34] developed equations that describe the SE as a function of type of PM, rainfall (P, mm), as well as concentrations of the pollutant before the rain (C,  $\mu\text{g.m}^{-3}$ ), these were expressed as follows:

$$SE_{PM2.5} = -66.6 + 1.4323P + 1.4241C - 0.0148P^2 - 0.0053C^2 + 0.0032P \times C \quad (14)$$

$$SE_{PM10} = -85.04 + 1.2770P + 1.8157C - 0.0126P^2 - 0.0070C^2 + 0.0024P \times C \quad (15)$$

These equations were applied to the period of interest. Daily rainfall data of Lahore city for that period were obtained from the United States National Oceanic and Atmospheric Administration (NOAA) website [35]. The concentration of the PM was changed from an hourly mean to a daily mean for this section.

#### Volatile organic compounds

Volatile organic compounds (VOC), particularly isoprene and monoterpene, also need to be considered in this context. Similarly to the SO<sub>2</sub>, NO<sub>2</sub>, O<sub>3</sub> gases, the VOC emissions were determined as discussed [19]. They are highly dependent on windspeed, air temperature, solar radiation and PAR. Reference [29] published emissions factors of isoprene and monoterpene for more than a 1000 individual trees specie in North America. They ranged from 0 to 70 and 0 to 8  $\mu\text{mol.m}^{-2}.\text{s}^{-1}$  for isoprene and monoterpene respectively. We are not aware that such values exist for local trees, and so we used 37 and 3.8  $\mu\text{mol.m}^{-2}.\text{s}^{-1}$  for isoprene and monoterpene respectively being in the top 5% of the published values.

#### SO<sub>2</sub> and NO<sub>2</sub> wet deposition

The wet deposition of both SO<sub>2</sub> and NO<sub>2</sub> in form of acid rain is not considered in this work. Rainfall during the winter months in Lahore is very limited given the climatic conditions, and as will be seen even the wash out of PM during rainfall events is minor, hence the wash out of SO<sub>2</sub> and NO<sub>2</sub> is not considered here. Workers such as [36] when comparing wet and dry deposition of SO<sub>2</sub> in a semi-arid environment confirmed this as they found that the latter far outweighed the former.

## 4. Results and Discussion

### GUS

Parts of several parks and the campus of FCCU in Lahore were assessed and the vegetation described and measured. A summary of the results of those measurements including the GUS and the Lahore Urban Area (LUA) are presented in Table 1.

The area covered in each park as part of this study was about 5 – 20 % of the total area of the parks and the campus. The areas selected in each park and the campus

were based on a visual assessment, containing a mix of typical park-scape attributes such as pathways, scrubs, furniture, water features and many trees. The focus of the assessment of parts of the parks and the campus was on trees which is obviously only a part, albeit significant, of the vegetation in the GUS. The species typically encountered consisted of species such as Peepal tree (*Ficus religiosa*), Shisham (*Dalbergia sisso*), Jaman (*Syzygiumcumini*), Beri pata (*Fernandoaadenophylla*), Arjun (*Terminalia Arjune*), Gaub (*Diospyros malabarica*), Neem (*Azadirachta indica*) and others. These trees are commonly found in the parks of Lahore as described by [37]. Forty-five to 90 % of the areas assessed, was covered by trees. The range in DBH was 0.15 to 1.2 m, the height of the trees ranged from about 4 m to 14 m. The largest amount of sun intercepted was about 0.95, while the lowest was about 0.4. The assessment of the parks was done in the June – August 2024, while the FCC campus was assessed in April – May 2024 hence most deciduous trees were in full canopy. The deciduous nature of some trees would render them not effective in removing pollutants during the winter months when the high levels of pollution occur. It was not determined what percentage of the trees were deciduous.

The total LA based on the CS was 95528 m<sup>2</sup>, and based on the DBH was 298305 m<sup>2</sup>. Two approaches to calculate the LA have been presented by [20], one based on the DBH and S and the other on the CS and S. Both yield a different LA; hence we presented the range of LAs here. Reference [20] whose equations we used, found a better R<sup>2</sup>(0.91) when using the CS method compared the DBH method for which he found a R<sup>2</sup> of 0.64. Reference [38] found that DBH alone accounted for 75 to 97 % of the variation in the LA in an oak-hickory forest. In our surveyed areas there is a great variety of species present hence the variation in DBH and the CS method of estimating the LA.

When comparing the LA derived using the Novak equations and estimated from our own leaf area estimates the best regression fit (R<sup>2</sup> = 0.93) was obtained when using the DBH method of estimating the LA. The CS method performed very poorly due to several odd-shaped trees. The LA used in the flux model, was derived from the DBH.

**Table 1. Descriptions of four parks in Lahore, the total areas of the parks, the areas measured, the number of trees in those areas, and the estimated leaf area based on CS and DBH. Estimated GUS1 and GUS2 (> 0.1 ha) and the LUA**

Park	TPA (ha)	AM (ha)	TA (%)	No trees	MDBH (m)	MTH (m)	MELA (m <sup>2</sup> )	ETLA (m <sup>2</sup> )
Lawrence	83.2	4.2	90	130	0.55	9.4	179 <sup>A</sup> 560 <sup>B</sup>	23292 <sup>B</sup> 72786 <sup>B</sup>
Nawaz Sharif	28.5	2.9	50	74	0.49	10.8	152 <sup>A</sup> 319 <sup>B</sup>	12171 <sup>A</sup> 32848 <sup>B</sup>
National Park	4.1	0.8	50	96	0.35	8.9	52 <sup>B</sup> 148 <sup>B</sup>	13453 <sup>A</sup> 42045 <sup>B</sup>
Jam-e-Sherin	12.4	2.4	80	186	0.44	9.6	90 <sup>A</sup> 267 <sup>B</sup>	21740 <sup>A</sup> 62224 <sup>B</sup>
FC College	50.0	13.1	45	619	0.20 168 <sup>B</sup>	5.2 88402 <sup>B</sup>	42 <sup>A</sup>	24872 <sup>A</sup>
LUA	54402	Fraction of LUA (%)			Total:	95528 <sup>A</sup>		
GUS1	536	0.98						298305 <sup>B</sup>
GUS2	933	1.7						

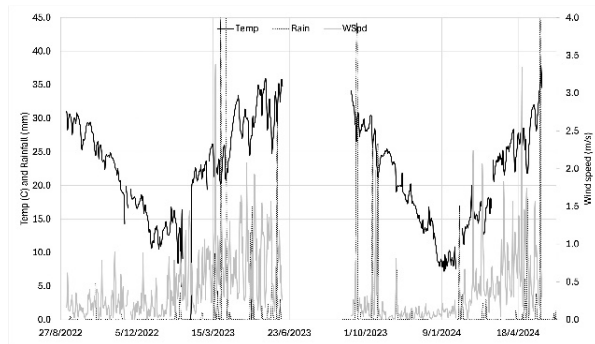
TPA = Total park area, AM: Area measured, TA: Area of the park covered by trees, MDBH: Mean diameter at breast height, MTH: Mean tree height, MELA: Median estimated leaf area per tree, ETLA = Estimated total leaf area for a given park. <sup>A</sup>: Leaf area based on CS, <sup>B</sup>: Leaf area based DBH

Reference [38] referred to the work of [39] who found for broad leaf forests a leaf surface area of 4 to 6 m<sup>2</sup>/m<sup>2</sup>. In our case that ratio ranged from 1.13 m<sup>2</sup>/m<sup>2</sup> for the more open park scape (National Park) to 2.58 m<sup>2</sup>/m<sup>2</sup> for the more densely treed park scape (Jam-e Shirin Park) using the DBH method for LA estimation.

The fraction of GUS of the LUA ranged from 0.98 (GUS1) to 1.7 % (GUS2). This fraction is based on the entire urban area, recognising that in many neighbourhoods one would struggle to find even a small area dedicated to GUS. In other neighbourhoods of Lahore, typically the more affluent neighbourhoods, more areas are identified as GUS.

#### Ambient weather and air quality at FC College in Lahore

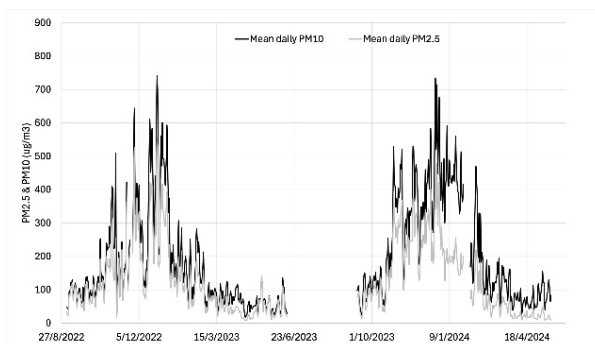
The mean daily ambient air temperature, rainfall and windspeed recorded at FCC in Lahore for the period under consideration (3 Sept 2022 – 10 June 2023, and 12 Sept 2023 – 19 May 2024) are presented in the following figure.



**Figure 2.** Daily mean rainfall, air temperature, and wind speed at the FC College campus in Lahore, Pakistan from the end of Aug 2022 until the middle of May 2024

The ambient weather conditions during the study period were typical of the weather in Lahore, where the climate is classified as BSh according to the Köppen classification system, which is described as a subtropical steppe climate [40]. During the winter months there is very little wind which also typical of the weather of the Indo-Gangetic Plain around November to February [41].

The mean daily PM<sub>2.5</sub> and PM<sub>10</sub> measured at the FCC for the same periods are presented in Figure 3.

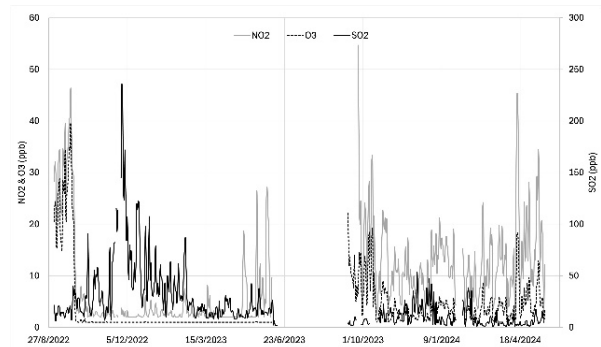


**Figure 3.** Mean daily PM<sub>2.5</sub> and PM<sub>10</sub> concentrations at the FC College campus in Lahore, Pakistan from the end of Aug 2022 until the middle of May 2024

Clearly the most pollution occurred during the winter months but considering the WHO guidelines for air quality, the PM<sub>2.5</sub> levels exceeded WHO guideline of 15

ug/m<sup>3</sup> [42] for a calendar year even during the less polluted months of the year.

Other pollutants such as NO<sub>2</sub>, SO<sub>2</sub> and O<sub>3</sub> measured with the FCC air quality monitor in Lahore are presented in Figure 4.



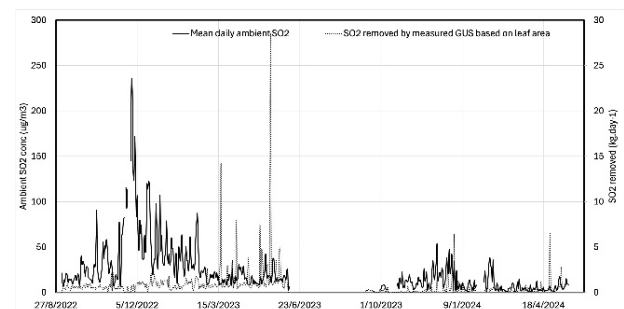
**Figure 4.** Mean daily concentrations of SO<sub>2</sub>, NO<sub>2</sub> and O<sub>3</sub> at the FC College campus in Lahore, Pakistan from the end of Aug 2022 until the middle of May 2024

The NO<sub>2</sub> and O<sub>3</sub> levels were relatively high coming out of the summer, but then moving into the winter months in 2022/23 the SO<sub>2</sub> levels started to increase, reaching a climax in early December 2023 and then gradually declining again towards the hotter part of the year. Until June 2024, this pattern was not repeated in 2023/24 when the NO<sub>2</sub> was higher. The O<sub>3</sub> levels were elevated coming out of summer and going into the summer both in 2023 and 2024.

#### Model outputs

The GUS description, the atmospheric conditions and the ambient air pollution parameters for the periods between 3/9/22 and 19/5/24 as presented in the previous section formed the input for the modelling component.

The amount of the SO<sub>2</sub> and NO<sub>2</sub> removed from the atmosphere by absorption by the tree canopies are presented in Figure 5 and Figure 6 respectively.



**Figure 5.** Mean daily ambient SO<sub>2</sub> concentration and the amount of SO<sub>2</sub> removed by the measured GUS in Lahore, Pakistan from the end of Aug 2022 until the middle of May 2024

Of interest is the lack of SO<sub>2</sub> and NO<sub>2</sub> removal by the vegetation during the winter months even though the ambient levels were high, certainly for the SO<sub>2</sub> in 2023. Earlier or later in the year the removal is more significant. The deposition velocities for both the NO<sub>2</sub> and SO<sub>2</sub> are governed by the stability classes. Based on the time of the day, the wind speed and the solar radiation the Obukhov length (L) was calculated which was usually negative (L < 0) during the day indicating unstable conditions while at night L > 0 indicating stable

conditions. As is shown in Figure 3, the wind speed is low during the winter months in Lahore while earlier or later in the year, particularly during May, Lahore is more prone to violent convection storms, particularly during the night, following high temperatures during the day [43]. Analysis of the timing of the wind speed confirmed that higher winds were more common during the night compared to the day. Higher wind speeds at night introduced more neutral conditions (Class D) instead of stable conditions (Class F) which influenced the deposition velocity ( $V_d$ ), hence the flux. Reference [7] in his study on vegetation as a sink for atmospheric pollutants found a strong positive correlation between the uptake of ozone and windspeed in their experimental setup. As they increased wind speed transpiration rates and  $CO_2$  uptake also increased which directly led to a higher uptake of pollutants.

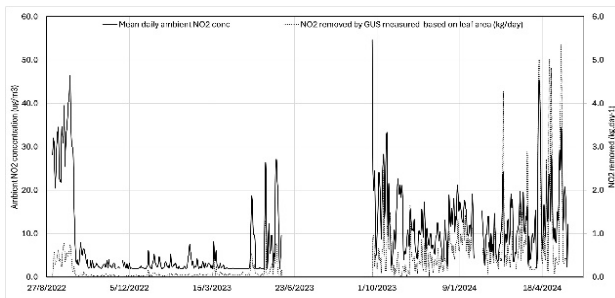


Figure 6. Mean daily ambient  $NO_2$  concentration and the amount of  $NO_2$  removed by the measured GUS in Lahore, Pakistan from the end of Aug 2022 until the middle of May 2024

The timing of the various stability classes throughout the year, except the summer, is presented in the following Figure 7. The timing is presented as the number of hourly observations of a given stability class (A – F) occurring during a given month for the two years.

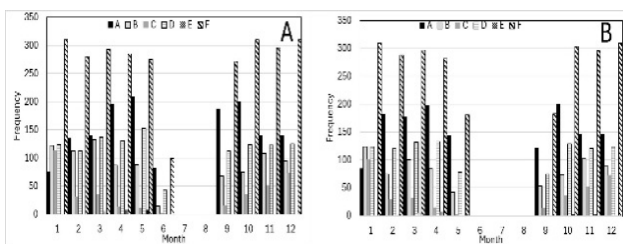


Figure 7. Frequency of hourly observations of specific stability classes for a given month for the period October 2022 till June 2023 (A) and for the period October 2023 till May 2024

Stability class, F, which is the most stable class was by far the most prominent class in both years, but particularly during the colder winter months, as the weather warmed up, the number of times stability class A, the most unstable class, occurred increased. Stable conditions are detrimental for the dispersal of the air pollution, hence the stability patterns would explain the prominence of the air pollution during the winter months.

The calculated removal of  $SO_2$  and  $NO_2$  was determined by the calculated deposition velocity ( $V_d$ ) multiplied by the ambient concentration of the pollutants ( $NO_2$  and  $SO_2$ ). Accordingly,  $V_d$  was calculated being on average  $0.003 - 0.004 \text{ m}\cdot\text{sec}^{-1}$  which agreed well with the values obtained by [18] who found  $V_d$  values of  $0.0037$  and  $0.0055 \text{ m}\cdot\text{sec}^{-1}$  for  $NO_2$  and  $SO_2$  respectively.

The removal of  $PM_{2.5}$  and  $PM_{10}$  from the atmosphere by dry deposition is presented in Figure 8.

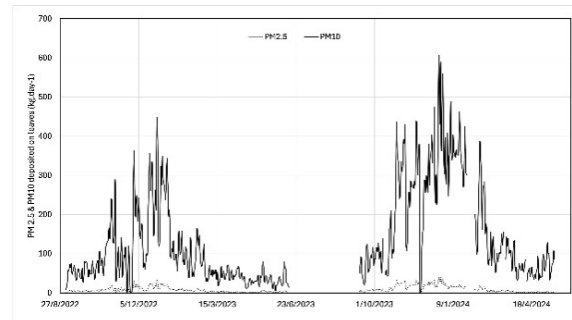


Figure 8. Daily amounts of  $PM_{2.5}$  and  $PM_{10}$  removed through the process of dry deposition based on the measured LA of observed GUS in Lahore, Pakistan from the end of Aug 2022 until the middle of May 2024

Also, here the dry deposition of the  $PM_{2.5}$  and  $PM_{10}$  was based on the ambient concentrations multiplied by the  $V_d$ . The  $V_d$  of the  $PM_{2.5}$  and  $PM_{10}$  were not calculated but taken from [32], being  $0.0032$  and  $0.032 \text{ m}\cdot\text{sec}^{-1}$  respectively. Reference [18] assumed a value of  $V_d$  of  $PM_{10}$  of  $0.0064$ .

The wet deposition of both  $PM_{10}$  and  $PM_{2.5}$  that occurs during rainfall is presented in Figure 9. This wet deposition is not dependent on the LA of the parks but solely on the rainfall and the pollutant concentration and the size of the area where the rainfall is received.

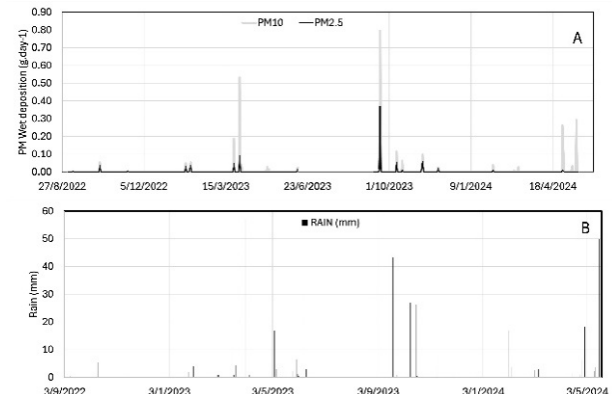
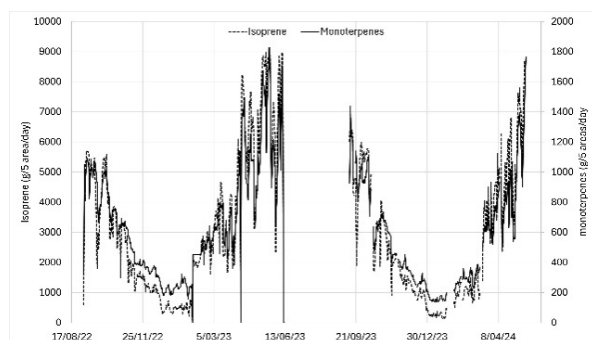


Figure 9. Wet deposition of  $PM_{10}$  and  $PM_{2.5}$  (A) through the process of scavenging during times of rainfall in Lahore, Pakistan from the end of Aug 2022 until the middle of May 2024

Here the wet deposition was based on the product of the ambient concentration and scavenging efficiency based on the published data by [34] which was based on the rainfall and the level of pollution before the rain. Scavenging efficiencies were described by [34] as polynomial functions with rainfall and level of pollution as dependent parameters. It was found the application of these factors published were only valid for pollution levels not exceeding  $150 \text{ }\mu\text{g}\cdot\text{m}^{-3}$ . When the pollution levels exceeded those amounts, the polynomials would be trending downwards and eventually become negative. In our case when the pollution levels exceeded  $150 \text{ }\mu\text{g}\cdot\text{m}^{-3}$  the polynomial factors would not change from the values obtained for  $150 \text{ }\mu\text{g}\cdot\text{m}^{-3}$ .

**VOCs**

The emissions of VOCs (isoprene and monoterpene) over the two years are presented in Figure 10.



**Figure 10.** VOCs emissions of isoprene and monoterpene for the 5 park areas in Lahore during the two year observation period

The emissions of VOCs are highest during the warm summer months while during the colder winter months the VOC emissions are at their minimum. The VOCs together with NO<sub>x</sub> are involved in the formation of ozone (O<sub>3</sub>) via a complex nonlinear photochemistry [44]. This becomes typically more significant during the warmer months of the year as VOC's concentration as well as the solar radiation increases. However, during the warmer months, the air quality in Lahore is of much less concern due to ambient atmospheric conditions, particularly the planetary boundary height layer (PBHL). The PBHL indicates the thickness of the layer closest to the surface of the earth where mixing of the air masses can occur and where the bulk of the air pollutants can be found. The thickness varies depending on the atmospheric conditions which are in turn governed by the times of the year. Typically in Lahore the PBHL drops to zero meters at night during the winter months while in the summer it can reach up to 2000 - 4000 m high [45].

#### Total pollutant removal

From the modelling effort, the impact of the five green areas on the removal of pollutants in Lahore was estimated as follows. From the sum of the calculated daily flux of the respective pollutants over the period of observation (3 Sept 2022 – 15 May 2024) the total weight removed of the respective pollutants was calculated and expressed as the percentage of the total weight of the pollutants present in the atmosphere. This is presented in Table 2. To determine the effect of GUS in Lahore, the impact of the sections of the parks was extrapolated to the larger GUS1 and GUS2 (see Table 1). The area of the parks and the FCCU area was 23.4 ha, while the area of Lahore was 54402 ha, while the height of the PBHL is assumed to be 100 m. This gives a volume of  $234 \times 10^5 \text{ m}^3$  and  $54402 \times 10^6 \text{ m}^3$  for the 5 green areas and Lahore respectively. To these volumes, ambient concentrations apply from which the total weight of the pollutants present could be calculated and are also presented in Table 2.

The PBLH is normally established with the use of a radiosonde balloon according to the method of [46]. Such balloons are not being released by the relevant Department in Lahore, hence we need to obtain the PBLH from other means such as the GDAS meteorological information (GDAS) and CAMS [47]. The PBLH is variable throughout the day and varies between 0 m at night and 2500 m at midday according to [45]. According to the CAMS observations the average PBLH is around 60 m during the winter months with little variation during the day, but significantly higher (3000 m) during the summer

months [47]. Combining the GDAS and the CAMS PBLHs an average PBLH of 100 m was assumed, being fully aware that changes to the PBLH affect the total sum of the pollutants present in the atmosphere. On the other hand, the PBLH is indirectly reflected in the concentrations of the PM<sub>2.5</sub> and PM<sub>10</sub> because they show a strong diurnal pattern based on emission variations but also on surface temperature variations which strongly influence the PBLH.

**Table 2.** Weight of pollutants (NO<sub>2</sub>, SO<sub>2</sub>, PM<sub>2.5</sub> and PM<sub>10</sub>) removed by the vegetation based on the LA present in the parks and the FC Campus and by the GUS1 and GUS2. The ambient concentrations are given as well as total mass of pollutants in the volume above the parks and FCCU as well as Lahore assuming PBLH of 100 m

Period		SO <sub>2</sub>	NO <sub>2</sub>	PM <sub>2.5</sub> dry	PM <sub>10</sub> dry
3 Sept 2022-11 June 2023	Mass removed (kg)	519	68	3873	52935
	Mass present (kg)	12365	957	18073	23514
	%	4	7	21	225
12 Sept 2023-19 May 2024	Mass removed (kg)	118	254	3877	66692
	Mass present (kg)	3121	4268	17719	30318
	%	4	6	22	220
3 Sept 2022 – 19 May 2024	Mass removed GUS1 (kg)	14168	7182	172474	266196
	Mass removed GUS2 (kg)	24661	1250	300220	463360
	Mass present in the atmosphere (kg)	$36 \times 10^6$	$12 \times 10^6$	$83 \times 10^6$	$125 \times 10^6$
	% GUS1	0.04	0.06	0.21	2.13
	% GUS2	0.07	0.10	0.36	3.71

The vegetation in the parks and the FCCU area removed 4 %, 7 %, 21 % and 225 % of SO<sub>2</sub>, NO<sub>2</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> respectively compared to what was present in the atmosphere. So, some of pollution is clearly removed due to absorption and dry deposition using the assumed input parameters with PM<sub>10</sub> largely being removed from the atmosphere. This shows the potential of the vegetation to play a role in cleaning the air. Reference [10] discussed the various factors influencing the role of the vegetation in air pollution removal. They noted the range of deposition velocity ( $V_d$ ) used by various groups of 0.002 – 35.7 cm.s<sup>-1</sup> whereas the magnitude was a function of the various vegetation parameters. Based on the work of [31,32,33] we used 0.032 and 0.0032 m.s<sup>-1</sup> for PM<sub>10</sub> and PM<sub>2.5</sub> respectively. Changing the  $V_d$  would have an immediate effect on the amount of PM deposited on the leaf areas. Incidentally the magnitude of 0.032 m.s<sup>-1</sup> we used, was supported by a study conducted on the campus of FCC (not published) where the amount of dust settling on hard impervious surfaces was tracked over a period of 2 months. The mean ambient PM<sub>10</sub> concentration measured in the vicinity of those surfaces was 124 µg/m<sup>3</sup> while the mean weight of dust in the form of total suspended particles (TSP) settling on the surfaces was 256 mg.m<sup>2</sup>.day<sup>-1</sup>. This resulted in a calculated flux of 0.0296 m.sec<sup>-1</sup>. For the TSP we did not distinguish between PM<sub>2.5</sub> and PM<sub>10</sub>.

The deposited mass of the pollutants by and on the vegetation is significant compared to the mass suspended in the space above the parks and the campus. However, the

impact of GUS reduces substantially when extrapolated to the metropolitan area of Lahore which has so little GUS. When the vegetated areas are extrapolated to GUS1 and GUS2, and the entire volume above the city is considered, then the amount of pollution removed by GUS2 is only 0.07 %, 0.1 %, 0.36 % and 3.7 % for NO<sub>2</sub>, SO<sub>2</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> respectively. This means that the pollution produced by the citizens of Lahore overwhelms the ability of the vegetation to remove these pollutants. Despite the ability of the vegetation to remove pollutants, it is clearly not enough. The GUS2 of the LUA was measured as 1.7% (see Table 2). If that was to increase to 10 % through a significant investment in creating green urban spaces populated with non-deciduous trees the absorbed pollution levels could, over time, become significant.

Reference [48] measured pollution levels in Lahore in a detailed study in different areas of Lahore and concluded that congestion was the culprit in areas where high levels of PM<sub>10</sub> were measured. Incidentally, those areas also coincide with neighbourhoods where vegetation is virtually non-existent (GUS = 0.3 %). Lower pollution levels were found in areas where also more vegetation (GUS = 19 – 25 %) is present which could support the findings presented in this paper.

In the current version of the model, there has not been an allowance for the impact of air pollution on the photosynthesis rates or efficiencies as reported by [49]. They found for all species, except one, a significant effect of the elevated pollution levels on the photosynthetic rates. The mean pollution rate they encountered in the city of Warsaw was 44.0 and 25.5 ug/m<sup>3</sup> for PM<sub>10</sub> and PM<sub>2.5</sub> respectively which is substantially lower than the levels encountered in Lahore as shown in this study. The impact of such high levels of pollution will have undoubtedly an effect of the photosynthetic rates but this needs to be quantified for the local conditions.

Reference [50] in their study on the fifth season in the country of Pakistan highlighted some of the solutions to the growing incidence of smog in the city of Lahore, these included the growing of trees. The figure included the number of 348,000 ha of trees planted through the Clean Green Initiative. While the actual area could be disputed, the Environmental Protection Agency of Punjab, Pakistan does see the need to increase the area planted to trees, or rather the creation of woodland in and around the major cities as stated in their policy on controlling smog [51]. The purpose of planting these trees as described in the policy is to “fix carbon and other noxious elements.”

This study has gone to some length to establish what the potential is when trees are planted in an environment burdened by severe air pollution. While the potential is present, a few other observations should be made. The lack of wind and limited hours of daylight during the period with the worst pollution limits the uptake of the pollutants to only a few hours per day. This limits the effectiveness of the vegetation as a sink. An increase in wind velocity during other times significantly increased the ability of the plants to absorb the gaseous pollutants but unfortunately this rarely happens during the winter months (Dec – Feb) which is normal for the Indo-Gangetic Plain [41]. An increase in the LA increases the opportunity for PM to settle down through dry deposition. Deciduous trees that lose their leaves during the worst

pollution period (i.e. winter) negate the benefits of vegetation for this form of removal of PM. For vegetation for pollution removal to be most beneficial, they should be non-deciduous.

## 5. Conclusion

The application of an air pollution model that incorporates the interaction with vegetation is essential if the effect of vegetation on air pollution is to be quantified. The preliminary results are in line with other reported values.

The determination of the LA is a significant factor in the outcome of the model. The flux is multiplied by the LA to determine the total quantity of pollutants removed or deposited. Changes in the LA directly impact the model outcomes. The LA was determined in the summer with the understanding that several of the tree species are deciduous which would affect the LA during the coldest months, the months with typically the highest pollution levels. It will need to be verified how the LA is affected during the winter months.

The outcome of the modelling efforts clearly illustrates that vegetation can absorb a significant amount of pollutants. However, despite the contribution the vegetation makes in terms of absorption and dry deposition of pollutants, the levels of pollution generated by the city of Lahore and the amount of vegetation in the city in terms of GUS, are such that little in-roads are made in combating air pollution. The modelling shows that environmental conditions during the winter months are also not very conducive for the uptake of air pollutants due to the absence of wind hence limiting the effectiveness of the role of vegetation as a sink. Dry deposition is not affected by the absence of wind.

This greater understanding of the role of vegetation in the city of Lahore in the context of pollution management should assist the policy makers of Punjab to make more informed decisions in the allocation, magnitude and the protection of green urban spaces. A local study such as this could be helpful in that decision making process.

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