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DEVELOPMENT OF AN APPLICABLE TREE AIR QUALITY BENEFIT CALCULATOR (PARS TAC) IN IRAN

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ABSTRACT

The Pars Tree Air $_{quality}$ Calculator v.1 (Pars TAC 1) was developed with a component-based modeling approach. Pars TAC takes a variety of data as its input and quantifies dry deposition of air pollutants in an area of interest based on its multiple resistance approach. Pars TAC outputs includes hourly results as well as summaries for longer periods for an area of interest. At last dry depositions of CO, NO2, O3, PM10, and SO2 in the National Park of Sorkheh-hesar have been estimated for 2010 by means of the resulted model and also compared with a number of similar studies' results.

Keywords: Urban Forest; Air-Pollutant; Dry Deposition; Mathematical Model; Pars TAC 1

INTRODUCTION

Air pollutants are removed from the atmosphere through a variety of mechanisms, including precipitation scavenging (i.e. wet deposition), chemical reaction, and direct deposition to terrestrial

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and marine surfaces in the absence of precipitation (i.e. dry deposition). With vegetation, gaseous air pollutants are removed through dry deposition primarily by uptake via leaf stomata(Nowak, Crane, and Stevens 2006, Cabaraban et al. 2013). Functions of the model were separated into components that are responsible for data input, user interface, core model functions and output. Pars TAC code was written in a Microsoft Excel-VBA file, while most of the input data (meteorological and pollution data) should be entered in a separate excel document which is linked to the former one. Input data includes monetary information, location related information, urban forest information, hourly meteorology and air pollutant concentration data. The monetary information includes social and external costs of five criteria air pollutants and the goal currency unit (e.g. 2012 US Dollars) fractional value in response to the user defined costs currency unit (e.g. 2010 US Dollars). The location information includes time zone, latitude, longitude, altitude and leaf-on and leaf-off dates. Urban forest characteristics include the maximum leaf area index (LAI) during the leaf-on season, tree coverage, and evergreen canopy percentages that can be used to approximate the minimum LAI during the leaf-off

season. The Meteorological information includes temperature, wind speed, air pressure, atmospheric stability, mixing height and etc. However atmospheric stability and mixing height can be estimated in the model when the corresponding data was not available.

Pars TAC provides a professional interface for experienced users, since a large number of constants and coefficients can be modified in its interface, without of any manipulation of the code, while by proposing normal ranges and typical amounts, not experienced users also can use it with easy.

MATERIAL AND METHODS

As it's mentioned above calculation of each component implemented separately. Model calculations comprised of following steps.

Solar calculations

Stomatal conductance is related to photosynthesis(Baldocchi 1994), thus it is related to solar radiation and temperature hence estimation of air pollutants dry deposition to vegetation requires for solar radiation data as an input. However obtaining such data may not be so easy in all conditions, esp. for developing countries. On other hand calculation of solar radiation based on solar position and sky conditions can be a meaningful easy procedure which

can resolve solar data requirements of a dry deposition model. The NOAA solar position calculator(NOAA 2013) is an excellent piece of JavaScript software which can be find online, however in order to use this software more easily, it is required to make it available offline and compatible with other components of the model too. The NOAA solar position calculator code could be written as an Excel-VBA application, then calculation of solar radiation could be done by means of one (or more) appropriate solar radiation prediction model(s). Bird and Hulstrom (Bird and Hulstrom 1991), Bras (Bras 1990) and Ryan and Stolzenbach's (Ryan and Stolzenbach 1972) models were used here. Extra-terrestrial radiation normal to the beam corrected for earth-sun distance variations and Julian day calculated by means of Bird and Hulstrom's model. Global radiation incident upon a horizontal surface (at user defined elevation) considered as an average of three aforementioned models. It is worth talking into consideration thatapproximately40% of the extra-terrestrial radiation is reflected back into space(Moan 2001).The remaining 60% includes several way lengths, however approximately 40 % of the radiation energy is visible light of wavelengths between 400 and 700 nm. About 8% of the radiation energy reaching the Earth's atmosphere is within the UV spectrum. At sea level, about 6% of the radiation is UV radiation, about 50% is visible radiation and about 40% is infrared radiation(Moan 2001). With regard to the large distance from the sea level to top of the atmosphere, considering a fraction of 6% for UV radiation on the Earth surface could be meaningful.

Dry deposition calculations:

The main role of Pars TAC is to calculate hourly dry deposition of CO, NO2, O3, PM10 and SO2 with hourly meteorological and pollutant measurements, location information, and urban forest parameters. A brief model description is included below. For a more complete description of each calculation Step, referenced documents could be used.

Models for estimating the dry deposition of air-pollutants are based on the so-called inferential method(Baldocchi, Hicks, and Camara 1987, Hicks et al. 1987, Padro, Zhang, and Massman 1998, Kramm et al. 1995, Walmsley and Wesely 1996, Padro 1996, Grunhage and Haenel 1997, Meyers et al. 1998, Brook et al. 1999, Emberson et al. 2000).In these models theozone deposition velocity is estimated as the reciprocal of the resistance. The models differ from each other in terms of their input data and

resistance parameterizations (Lagzi et al. 2004).

Pollutant flux, F ($g.m^{-2}. s^{-1}$), is estimated as a product of the dry deposition velocity, V_d ($m. s^{-1}$) in height Z or $V_d(z)$, and the air pollutant concentration, C ($g.m^{-3}$) at deposition surface (C_s) and in height Z or C(z) (Bartnicki et al. 1999):

$$F = V_{d(Z)}. \left[C_{(Z)} - C_S \right] (1)$$

By consideration of a zero concentration at deposition surface, this equation could be simplified to(Hirabayashi, N. Kroll, and Nowak 2011, Hirabayashi, Charles.N.Kroll, and J.Nowak 2011):

$$F = V_d. C \quad (2)$$

V_d for PM_{10} calculated based on

V_d for each gaseous species were estimated as the inverse of the sum of resistances to pollutant transport (Baldocchi, Hicks, and Camara 1987, Wesely and Hicks 2000, Hirabayashi, N. Kroll, and Nowak 2011, Lagzi et al. 2004):

$$V_d = (R_a + R_b + R_c)^{-1} \quad (3)$$

Where R_a represents air movement resistance in the crown space(aerodynamic resistance), R_b represents transfer resistance throughthe boundary layer immediately adjacent to canopy surfaces(quasi-laminar boundary layer resistance), and R_c represents thechemical and biological absorption capacity of the canopy surfaces(canopy resistance)(Hirabayashi, N. Kroll, and Nowak 2011). R_a is calculated as(Killus et al. 1984, Authority 2005):

$$R_a = \frac{u_{(z)}}{u_*^2} \quad (4)$$

Where u(z) is the mean wind speed at height z, and u_* is the friction velocity calculated as a function of u(z), surface roughness, displacement length, and Monin–Obukhov length, depending upon atmospheric stability(EPA 1976, Authority 2005, Dyer and Bradley 1982, Fleagle and Businger 1980). The friction velocity is introduced as a shorthand notation of square-root of the kinematic stress and does not provide new physical insight, but it may be used as a convenient scaling velocity. Kinematic stress is the stress divided by the density of air(Fleagle and Businger 1980, CAOPS 2014). Estimation of the mixing height and u_* implemented under different stability conditions with accord to relevant appropriate methods (Zilitinkevich 1972, Pegahfar, Aliakbari-Bidokhti, and Zawar-Reza 2011, Authority 2005, Fatogoma and Jacko 2002, Seibert et al. 1997, EPA 1992, Victoria 2012). R_b is calculated as(Pederson et al. 1995, Bartnicki et al. 1999, Hirabayashi, Charles.N.Kroll, and J.Nowak 2011, Hicks et al. 1987):

$$R_b = 2(Sc)^{2/3} \times (Pr)^{-2/3} \times (ku_*)^{-1}$$
(5)

Where Sc is the Schmidt number, Pr is the Prandtl number (=0.72), and k isthe von Karman constant (=0.41).

Hourly R_C for NO2, O3, and SO2 is calculated based the corrected Hicks model canopy stomatal resistance (CSR) two-big-leaf model(Zhang, Moran, and Brook. 2001, Hicks et al. 1987). The canopy resistance (R_C)depends on four components: stomatal resistance (r_s), mesophyll resistance (r_m),cuticular resistance (r_t), and soil resistance (r_{soil}) (Hirabayashi, Charles.N.Kroll, and J.Nowak 2011) :

$$\frac{1}{R_c} = \frac{1}{r_s + r_m} + \frac{1}{r_t} + \frac{1}{r_{soil}}$$
(6)

The mesophyll resistance (r_m) is calculated as(Hirabayashi, Kroll, and Nowak 2012)

$$r_m = \frac{r_{baseM}}{LAI}$$
(7)

Where

r_{baseM} = Base mesophyll resistance

The cuticular resistance (r_t) is calculated as (Hirabayashi, Charles.N.Kroll, and J.Nowak 2011, Service 2014)

$$r_t = \frac{r_{baseC} \times \frac{D_v}{D}}{2 \times LAI}$$
(8)

Where

r_{baseC} = Base cuticular resistance

D_v = Water vapor diffusivity (=0.2178cm^2/s)

D = Molecular diffusivity of the pollutant

Table 1 shows the appropriate base values of r_m (r_{baseM}) and r_t (r_{baseC}) for NO$_2$, O$_3$ AND SO$_2$ respectively (Hirabayashi, Charles.N.Kroll, and J.Nowak 2011, Hirabayashi, N. Kroll, and Nowak 2011, Service 2014).

LAI is defined as half of the total area of leaves per unit ground surface area projected on the horizontal datum (Jonckheere et al. 2004, Jonckheere et al. 2003).

Derivation of stomatal conductance, g$_S$, theinverse of r$_S$, is based on its link to leaf photosynthesis. G$_S$ can beexpressed is as a function of incident photosynthetically active radiation (PAR) and some correction factors(Baldocchi, Hicks, and Camara 1987, Hicks et al. 1987, Turner and Begs 1973, Zhang et al. 2002).

$$R_{st} = 1 \left/ \left[G_s(PAR)f(T)f(D)f(\psi) \frac{D_i}{D_v} \right] \right.$$
(9)

Where G$_S$(PAR) is the total canopy stomatal conductance(i.e., the inverse of stomatal resistance), the dimensionless functions f(T), f(D) and f(Ψ) represent the influence of air temperature (T), water vapor pressure deficit (D), and water stress (leaf water potential,

Ψ), respectively, and D_V and D_i are the molecular diffusivities for water vapor and the pollutant gas, respectively (Zhang, Moran, and Brook. 2001, Baldocchi, Hicks, and Camara 1987, Baldocchi 1994, Jarvis 1976, Zhang et al. 2002) . This equation can be expanded to incorporate additional effects (such as the physiological effects of other pollutants) by introducing further multiplicative factors(Baldocchi, Hicks, and Camara 1987).

Table 1: The appropriate base values of r_m (r_{baseM}) and r_t (r_{baseC})

Pollutant	NO$_2$	O$_3$	SO$_2$
r_{baseM}	600 (sm^{-1})^2	60 (sm^{-1})^2	0 (sm^{-1})^1
R_{baseC}	20000 (sm^{-1})^4	10000 (sm^{-1})^3	8000 (sm^{-1})^3
Molecular diffusivity	0.1361(cm^2 s^{-1})^5	0.1444(cm^2 s^{-1})^5	0.1119(cm^2 s^{-1})^5

however the accuracy ofthe calculations is not in direct correlation with thecomplexity of the models, since there are uncertainties inthe chemical, physical and biological processes governingthe air pollutants flux(Zhang, Moran, and Brook. 2001). Furthermore as stomatal resistance is relatively independent of Ψ, until it drops

1Derived from)Wesely 1989(
2Derived from)Hosker and Lindberg 1982(
3Derived from)Lovett 1994, Taylor Jr., Hanson, and Baldocchi 1988(
4Derived from)Wesely 1989(
5Derived from)Service 2014(

below a threshold value(Hicks et al. 1987) and also as it is not easy to obtain required data for calculation of water vapor deficit in Iran, stomatal resistance is calculated with out of water stress effect considerations, here.

$$R_{st} = 1 \left/ \left[G_s(PAR)f(T)\,{D_i}/{D_v} \right] \right. \quad (10)$$

Since leaf stomatalconductance varies with PAR, G_{st} is calculated as theweighted sum of conductances for sunlit and shadedleaves(Hicks et al. 1987, Zhang et al. 2002, Zhang, Moran, and Brook. 2001, Lagzi et al. 2004):

$$G_s(PAR) = \frac{LAI_{Sun}}{r_s(PAR_{Sun})} + \frac{LAI_{Shade}}{r_s(PAR_{Shade})} \quad (11)$$

r_{St}(PAR) for sunlit and shaded leaves calculated as(Hicks et al. 1987, Zhang et al. 2002, Zhang, Moran, and Brook. 2001, Lagzi et al. 2004):

$$r_s(PAR) = r_{s\,min}\left(1 + \frac{b_{rs}}{PAR}\right) \quad (12)$$

Where LAI_{sun} and LAI_{shade} are the total sunlit and shaded leafarea indexes (LAIs), respectively, PAR_{sun} and PAR_{shade} are PAR received by sunlit and shaded leaves, respectively, r_{St} is the unstressed leaf stomatal resistance, $r_{St,\,min}$is the minimum leaf stomatal resistance which varies with

the plant species,and b_{rs} is anempirical constant (equal tothe *PAR flux* density at twice the minimum stomatal resistance),also species-dependent(Baldocchi, Hicks, and Camara 1987, Baldocchi 1994, Brook et al. 1999, Zhang, Moran, and Brook. 2001, Zhang et al. 2002). Several researches implemented to provide a comprehensive survey ofminimum stomatal resistances of many native andcultivated plants(Korner, Scheel, and Bauer 1979, Korner and Bannister 1985, Pospisilova and Sotarova 1980, Solarova and Pospisilova 1979).

Following expressions used for estimation ofLAI$_{sun}$ and LAI$_{shade}$(Norman 1982, Zhang, Moran, and Brook. 2001, Zhang et al. 2002, Baldocchi, Hicks, and Camara 1987):

$$LAI_{Sun} = 2cos\theta \times \left(1 - e^{\left(-\frac{0.5\,LAI}{cos\theta}\right)}\right)$$
(13)

$$LAI_{Shade} = LAI - LAI_{Sun} \qquad (14)$$

The expressions for PAR $_{sun}$ and PAR $_{shade}$ are modified from Norman (Norman 1982) as discussed in Zhang et al.(Zhang, Moran, and Brook. 2001, Zhang et al. 2002). For LAI <2.5 or solar radiation <200 W.m^2 :

$$PAR_{Shade} = \left(R_{diff} \times e^{-0.5LAI^{0.7}}\right) +$$
$$(0.07R_{dir}(1.1 - 0.1LAI) \times e^{-cos\theta}$$
(15)

$$PAR_{Sun} = \left(R_{dir} \times \frac{cos\alpha}{cos\theta}\right) + PAR_{Shade} \qquad (16)$$

For all other conditions:

$$PAR_{Shade} = \left(R_{diff} \times e^{-0.5LAI^{0.8}}\right) +$$
$$(0.07R_{dir}(1.1 - 0.1LAI) \times e^{-cos\theta} \qquad (17)$$

$$PAR_{Sun} = \left(R_{dir}^{0.8} \times \frac{cos\alpha}{cos\theta}\right) + PAR_{Shade}$$
(18)

Where LAI is the leaf area index of the canopy, ɵ is the solar zenith angle, and α is the angle between the leaf and the sun and has a value of 60° for a canopy assumed to have a spherical leaf angle distribution. R $_{diff}$ and R $_{dir}$ are the downward visible radiation fluxes above the canopy from diffuse and direct-beam radiation, respectively(Zhang et al. 2002, Zhang, Moran, and Brook. 2001). Weiss and Norman developed formulas for calculating R $_{diff}$ and R $_{dir}$ from measured global incoming solar radiation(Weiss and Norman. 1985, Irmak et al. 2008, Zhang et al. 2002, Zhang, Moran, and Brook. 2001, Hirabayashi, Charles.N.Kroll, and J.Nowak 2011, Hirabayashi, N. Kroll, and Nowak 2011) and these formulas modified here with site specific steady state calculated extra-terrestrial and global radiation incident upon a horizontal surface (at user defined elevation) assuming that about 8 and 6 percent of the radiation energy is within the UV spectrum at top of the atmosphere and at the Earth surface respectively .

Air quality improvement calculation

Hourly air quality improvement per unit tree cover due to the dry deposition of air pollutants, I_{unit} (%) is calculated as(Hirabayashi, Charles.N.Kroll, and J.Nowak 2011):

$$I_{unit} = \frac{F}{F + M_{total}} \times 100 \qquad (19)$$

where

F = Pollutant flux (g m^{-2} h^{-1})

M_{total} = Total air pollutant mass per unit tree cover (g m^{-2})

$$M_{total} = H.C \qquad (20)$$

where

C = Air pollutant concentration (g m^{-3})

H = Urban mixing height (m)

H is depended on the atmospheric stability and some other factors. Atmospheric stability and the urban mixing height both can be identified as an input by the user or to be estimated with appropriate methods by the model.

Hourly air quality improvement for total tree cover, I_{total} (%) is calculated as(Hirabayashi, Charles.N.Kroll, and J.Nowak 2011):

$$I_{total} = I_{unit} \times \frac{T_c}{100} \qquad (21)$$

where

T_c = Total tree cover in the city (%)

Monetary value calculation

Monetary value of pollution removal by trees is estimated using the median externality and social damage values for each pollutant. These values should be identified by user. A special coefficient for exchanging the cost currency unit (e.g. 2010 US Dollar) to user defined currency unit (e.g. 2012 US Dollar) can also be identified by user.

RESULTS

The main output of this study was the Pars TAC model. Air-quality improvement due to dry depositions of CO, NO2, O3, PM10, and SO2 in the National Park of Sorkheh-hesaralso evaluated using Pars TAC. The main purpose for this case study was to examine the Pars TAC applicability in Iran. It was shown that this model is an appropriate and simple model for modeling of air pollutant removal by dry deposition to urban trees in Iran. Cost values from(Hirabayashi, Charles.N.Kroll, and J.Nowak 2011, Hirabayashi, Kroll, and Nowak 2012, Rogers et al. 2011, Rogers, Jarratt, and Hansford. 2011) and currency coefficient from a GDP (Gross Domestic Product) deflator-based calculator(areppim 2013) were used in the case study. The air-pollutants dry deposition and their respective air-quality improvements are shown in table 2.

Table 2: Air quality improvement and pollution removal in Sorkheh-hesar

Pollutant	Removal			Air-quality improvement (2010 average)	External cost value(Average, 2010 $)	Social damage value(Average, 2010 $)
	Minimum	Average	Maximum			
PM10	175.56	280.89	456.45	4.79	1932116	12470242
NO2		191.73		0.55	1975290	288736
O3		184.23		0.69	1897989	277437
SO2		143.08		0.91	360856	368594
CO		45.25		0.01	66209	

DISCUSSION

Pars TAC formulation is composed of a large number of relations among astronomical, meteorological and vegetation parameters. This formulation formed as a combination of conventional or approved formulas which have been used widely in other deposition models before. With regard to long-establishment of these formulas, discussion of those not included here. However as the Pars TAC model is a new model for estimation of air-quality improvements of trees, its resulted data for Sorkheh-hesar national park compared with results of similar studies and sources of their differences discussed here.

With accord to table 3 it can be comprehended that in compare to Torbay, Sorkheh-hesar has a higher pollution removal capacity on both its surface area and surface area of its foliages. Again and in compare with London site, Sorkheh-hesar

has shown a higher PM$_{10}$ removal capacity on its surface area. Guangzhou also had a lesser pollution removal capacity on its surface area in compare to Sorkheh-hesar. Standardized pollution removal rate of Chicago green roofs was lesser than that belongs to Sorkheh-hesar. However standardized pollution removal rate of Beijing site was much more than Sorkheh-hear one. The annual pollution removal by trees in 55 US cities also shows a wide range variation between different cities pollution removal rates which ranged from 2-30(Nowak, Crane, and Stevens 2006)**.** Again removal rates in US cities were more or less different from to those for Sorkheh-hesar. Nevertheless some of these differences can be explained by contrasting canopy cover, different meteorological data, disparate ambient pollution concentration and diversities of total and evergreen leaf area between these sites.

Table 3: Pollution removal and its related information for several study sites

Parameter / Study Site	LAI	P.R/LA(g.yr-1.m-2)	P.R/S.A	PM10.R/LA	PM10.R/S.A	Std P.R
Sorkheh-hesar	3.1	3.3	9.21	1.0974	3.06	12.8
Torbay[1]	0.81	0.967	0.2	0.348	0.07	
London[2]	16				0.9	
Guangzhou[3]	Agricultural: 1.3 / Forest: 8.9		2.3			
Beijing[4]						27.5
Chicago green roofs[5]						8.5

Table 4 shows estimated air-quality improvements in eleven selected US cities and Sorkheh-hesar.

Site	% tree cover	% air quality improvement					
		CO	NO$_2$	O$_3$	PM$_{10}$	SO$_2$	Total
Atlanta, GA	32.9	0.002	0.5	0.7	0.7	0.7	2.6
Boston, MA	21.2	0.002	0.4	0.6	0.6	0.5	2.1
Dallas, TX	28	0.002	0.4	0.6	0.6	0.6	2.2
Denver, CO	26	0.001	0.2	0.3	0.4	0.3	1.2
Milwaukee, WI	19.1	0.001	0.3	0.4	0.4	0.4	1.5
New York, NY	16.6	0.001	0.3	0.4	0.5	0.4	1.6
Portland, OR	42	0.003	0.6	0.8	1.0	0.7	3.1
San Diego, CA	8.6	0.001	0.2	0.3	0.3	0.3	1.1
Tampa, FL	9.6	0.001	0.2	0.2	0.2	0.2	0.8
Tucson, AZ	13.7	0.001	0.1	0.1	0.2	0.1	0.5
Washington, DC	31.1	0.002	0.4	0.6	0.7	0.6	2.3
Sorkheh-hesar	90	0.01	0.55	0.69	4.79	0.91	6.95

[1] From reference (Rogers, Jarratt, and Hansford. 2011, Rogers et al. 2011)
[2] From reference(Tiwary et al. 2009)
[3] From reference (Jim and Chen 2009)
[4] From reference(Yang et al. 2005)
[5] From reference(Yang, Yu, and Gong. 2008)

According to table 4 it can be stated that study sites with greater tree cover often shows more air-quality improvements, however there are some exceptions for this statement. For example Denver has a greater tree cover in compare to Boston, Milwaukee and New York, but its air-quality improvement is lesser than those ones. Again tree cover in Tucson is more than Tampa and San Diego, yet both of them have shown higher values of air-quality improvement in respect to Tucson. On other hand tree cover in Sorkheh-hesar is approximately three times of Washington's one and its air-quality improvement also holds the same proportion.

CONCLUSIONS

In this study Pars TAC model developed in order to evaluate air-quality improvements by urban forest. For expansion of model functionality, instead of taking some fixed values into consideration for some basic coefficients and constants used in the model's equations, user can identify the appropriate value based on his/her investigations. However a brief guidance including the parameter's typical range is provided besides this parameter's input cell. It has been attempted to minimize Pars TAC model's complexity and data requirements as much as reasonable. However there are some optional input-data which can be provided by user or leaved blank to be estimated by the model. Since a separate excel file is provided for meteorological and air-pollution data, Pars TAC user interface becomes as succinct as possible. It is possible that user provided data for some numerical parameters also includes some not numerical contents (e.g. "n.a.", ".","*", n/a"), for such an input, it's value considered as unknown and replaced by interpolation. Yet because this error recognition ability is limited, it is recommended for user to avoid such errors. A field survey also implemented and dry depositions of CO, NO2, O3, PM10, and SO2 in the National Park of Sorkheh-hesarevaluated using Pars TAC. By implementation of the case study it was shown that the Pars TAC model is a simple and appropriate model for evaluation of air-quality benefits of trees in Iran.

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