

# Urban Forest Effects-Dry Deposition (UFORE –D)

## Model Descriptions

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### 1. Introduction

The Urban Forest Effects (UFORE) is a computer model implemented in SAS (Statistical Analysis Software) that utilizes field-surveyed urban forest information, location specific data, weather data, and air pollutant measurements to quantify urban forest structure and numerous forest-related effects. UFORE-D (Dry Deposition) is a part of UFORE that quantifies dry deposition of air pollution (i.e., pollution removal during nonprecipitation periods) to trees and shrubs and associated percent improvement in air quality throughout a year. The dry deposition of six criteria air pollutants (CAPs); carbon monoxide (CO), nitrogen dioxide (NO<sub>2</sub>), ozone (O<sub>3</sub>), sulfur dioxide (SO<sub>2</sub>), and particulate matter less than 10 microns (PM10) and 2.5 microns (PM2.5) can be processed. This document provides detailed UFORE-D model descriptions.

### 2. Model Descriptions

UFORE-D provides functions to calculate values listed below. These functions are described in this section.

- Air pollutant flux calculation
- Deposition velocity calculation
- Aerodynamic resistance calculation
- Friction velocity calculation
- Quasi-laminar boundary layer resistance calculation
- Canopy resistance calculation
- Stomatal resistance calculation
- Transpiration calculation
- Air quality improvement calculation
- Monetary value calculation

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## 2.1. Air pollutant flux calculation

Pollutant flux is calculated as a product of the deposition velocity and the air pollutant concentration:

$$F = V_d \times C \quad (1)$$

$$F_{Min} = V_{d,Min} \times C \quad (2)$$

$$F_{Max} = V_{d,Max} \times C \quad (3)$$

where

$F$	=	Pollutant flux ( $\text{g m}^{-2} \text{s}^{-1}$ )
$F_{Min}$	=	Minimum pollutant flux ( $\text{g m}^{-2} \text{s}^{-1}$ )
$F_{Max}$	=	Maximum pollutant flux ( $\text{g m}^{-2} \text{s}^{-1}$ )
$V_d$	=	Deposition velocity ( $\text{m s}^{-1}$ )
$V_{d,Min}$	=	Minimum deposition velocity ( $\text{m s}^{-1}$ )
$V_{d,Max}$	=	Maximum deposition velocity ( $\text{m s}^{-1}$ )
$C$	=	Air pollutant concentration ( $\text{g m}^{-3}$ )

## 2.2. Deposition velocity calculation for CO, NO<sub>2</sub>, SO<sub>2</sub>, and O<sub>3</sub>

Deposition velocities ( $V_d$ ) for CO, NO<sub>2</sub>, SO<sub>2</sub>, and O<sub>3</sub> are calculated as the inverse of the sum of the aerodynamic resistance ( $R_a$ ), quasi-laminar boundary layer resistance ( $R_b$ ), and canopy resistance ( $R_c$ ) (Baldocchi et al. 1987). The aerodynamic resistance can be calculated with meteorological data and thus is independent of the air pollutant types, while the quasi-laminar boundary layer and canopy resistances are separately calculated for CO, NO<sub>2</sub>, O<sub>3</sub>, and SO<sub>2</sub>. In addition, the canopy resistance is calculated depending on in-leaf and out-of-leaf periods.

### 2.2.1. In-leaf periods

$$V_d = \frac{1}{R_a + R_b + R_{c,InLeaf}} \quad (4)$$

where

$V_d$	=	Deposition velocity ( $\text{m s}^{-1}$ )
$R_a$	=	Aerodynamic resistance ( $\text{s m}^{-1}$ )
$R_b$	=	Quasi-laminar boundary layer resistance for a type of air pollutions ( $\text{s m}^{-1}$ )
$R_{c,InLeaf}$	=	Canopy resistance in in-leaf periods ( $\text{s m}^{-1}$ )

Depending on the flux density of photosynthetically active radiation (PAR), minimum and maximum of  $V_d$  are estimated as follows (Lovett 1994):

If  $PAR > 0$  (in the daytime)

for  $NO_2$

$$\begin{aligned} V_{d,Min} &= 0.001 \\ V_{d,Max} &= 0.005 \end{aligned} \quad (5)$$

for  $O_3$

$$\begin{aligned} V_{d,Min} &= 0.001 \\ V_{d,Max} &= 0.008 \end{aligned} \quad (6)$$

for  $SO_2$

$$\begin{aligned} V_{d,Min} &= 0.002 \\ V_{d,Max} &= 0.01 \end{aligned} \quad (7)$$

else (in the nighttime)

$$\begin{aligned} V_{d,Min} &= V_d \\ V_{d,Max} &= V_d \end{aligned} \quad (8)$$

### 2.2.2. Out-of-leaf periods

$$V_d = \frac{1}{R_a + R_b + R_{c,OutLeaf}} \quad (9)$$

$R_{c,OutLeaf}$  = Canopy resistance in out-of-leaf periods ( $s\ m^{-1}$ )

## 2.3. Deposition velocity calculation for PM10

### 2.3.1. In-leaf periods

Deposition velocity for PM10 is calculated based on average, minimum, and maximum values reported by Lovett (1994).

$$V_d = V_{d,PM,Avg} \times \frac{BAI + LAI}{BAI + LAI_{PM10}} \quad (10)$$

$$V_{d,Min} = V_{d,PM,Min} \times \frac{BAI + LAI}{BAI + LAI_{PM10}} \quad (11)$$

$$V_{d,Max} = V_{d,PM,Max} \times \frac{BAI + LAI}{BAI + LAI_{PM10}} \quad (12)$$

where

- $V_{d,PM,Avg}$  = Average deposition velocity for PM10 (= 0.64 ms<sup>-1</sup>) (Lovett 1994)  
 $V_{d,PM,Min}$  = Minimum deposition velocity for PM10 (= 0.25 ms<sup>-1</sup>) (Lovett 1994)  
 $V_{d,PM,Max}$  = Maximum deposition velocity for PM10 (= 1.00 ms<sup>-1</sup>) (Lovett 1994)  
 $LAIPM10$  = Leaf area index for particle deposition (= 6)  
 $BAI$  = Bark area index  
 $LAI$  = Leaf area index

### 2.3.2. Out-of-leaf periods

$$V_d = V_{d,PM,Avg} \times \frac{BAI + LAI_{evergreen}}{BAI + LAI_{PM10}} \quad (13)$$

$$V_{d,Min} = V_{d,PM,Min} \times \frac{BAI + LAI_{evergreen}}{BAI + LAI_{PM10}} \quad (14)$$

$$V_d = V_{d,PM,Max} \times \frac{BAI + LAI_{evergreen}}{BAI + LAI_{PM10}} \quad (15)$$

where

- $LAI_{evergreen}$  = Leaf area index for evergreen vegetation

## 2.4. Aerodynamic resistance calculation

The aerodynamic resistance ( $R_a$ ) is calculated as (Killus et al. 1984):

$$R_a = \frac{u(z)}{u_*^2} \quad (16)$$

where

$$\begin{aligned}
 u(z) &= \text{Mean wind speed at height } z \text{ (ms}^{-1}\text{)} \\
 u_* &= \text{Friction velocity (ms}^{-1}\text{)}
 \end{aligned}$$

## 2.5. Friction velocity calculation

Depending on the stability of atmosphere (i.e., neutral, unstable, and stable),  $u_*$  is calculated as described in the following sections. The stability of atmosphere can be determined by Monin-Obuhkov stability length, which can be empirically estimated based on the Pasquill stability class.

$$\begin{aligned}
 \text{Pasquill = A: } 1/L &= -0.0875 \times z_o^{-0.1029} \\
 \text{B: } 1/L &= -0.03849 \times z_o^{-0.1714} \\
 \text{C: } 1/L &= -0.0807 \times z_o^{-0.3049} \\
 \text{D: } 1/L &= 0 \times z_o^0 \\
 \text{E: } 1/L &= 0.0807 \times z_o^{-0.3049} \\
 \text{F: } 1/L &= 0.03849 \times z_o^{-0.1714}
 \end{aligned} \tag{17}$$

where

$$\begin{aligned}
 L &= \text{Monin-Obuhkov stability length} \\
 z_o &= \text{Roughness length}
 \end{aligned}$$

### 2.5.1. Neutral atmosphere (L=0)

For the neutral atmosphere,  $u_*$  is calculated as:

$$u_* = \frac{(k \times u(z-d))}{\ln\left(\frac{z-d}{z_o}\right)} \tag{18}$$

where

$$\begin{aligned}
 k &= \text{von Karman constant (=0.41)} \\
 u(z) &= \text{Mean wind speed at height } z \text{ (m s}^{-1}\text{)} \\
 z &= \text{Height of the weather station (m)} \\
 d &= \text{Displacement height (m)} \\
 z_o &= \text{Roughness length (m)}
 \end{aligned}$$

### 2.5.2. Unstable atmosphere (L < 0)

When the atmosphere is unstable such as during daytime when the air convection occurs,  $u_*$  is calculated as (Killus

et al. 1984):

$$u_* = \frac{(k \times u(z-d))}{\ln\left(\frac{z-d}{z_o}\right) - \Psi_M\left(\frac{z-d}{L}\right) + \Psi_M\left(\frac{z_o}{L}\right)} \quad (19)$$

where

$\Psi_M$  : Stability function for momentum

$L$  : Monin-Obuhkov stability length

Stability function for momentum ( $\Psi_M$ ) is calculated as (van Ulden and Holtslag 1985):

$$\Psi_M = 2 \ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2 \tan^{-1}(x) + \frac{\pi}{2} \quad (20)$$

where x is calculated as (Dyer and Bradley 1982):

$$x = \frac{1}{(1-28z/L)^{0.25}} \quad (21)$$

### 2.5.3. Stable atmosphere ( $L > 0$ )

When the atmosphere is stable  $u_*$  is calculated as (Venkatram 1980):

$$u_* = C_{DN} \times u(z) \left\{ \frac{1}{2} + \frac{1}{2} \sqrt{1 - \left( \frac{2u_o}{\sqrt{C_{DN}} \times u(z)} \right)^2} \right\} \quad (22)$$

where

$C_{DN}$  = Neutral drag coefficient (dimensionless)

$C_{DN}$  is calculated as (US EPA 1995):

$$C_{DN} = \frac{k}{\ln\left(\frac{z}{z_o}\right)} \quad (23)$$

$u_o$  is calculated as (US EPA 1995):

$$u_o = \sqrt{\frac{\beta_m z g \theta_*}{T}} \quad (24)$$

where

$\beta_m$  = Dimensionless constant (= 4.7)

$g$  = Acceleration due to gravity (= 9.81 ms<sup>-2</sup>)

$T$  = Air temperature (K)

$\theta_*$  is calculated as (US EPA 1995)

$$\theta_* = 0.09(1 - 0.5N^2) \quad (25)$$

where

$N$  = Fraction of opaque cloud cover

To obtain real-valued solutions for  $u_*$ , the following condition must hold

$$\frac{2u_o}{\sqrt{C_{DN}} \times u(z)} \leq 1 \quad (26)$$

Otherwise, the friction velocity ( $u_*$ ) is calculated as (US EPA 1995):

$$u_* = u_{*cr} \frac{u(z)}{u_{cr}} \quad (27)$$

where  $u_{cr}$  and  $u_{*cr}$  are calculated as (US EPA 1995):

$$u_{cr} = \sqrt{\frac{4}{C_{DN}}} u_o \quad (28)$$

$$u_{*cr} = \frac{C_{DN} u_{cr}}{2} \quad (29)$$

## 2.6. Quasi-laminar boundary layer resistance calculation

Quasi-laminar boundary layer resistance ( $R_b$ ) is calculated as (Pederson et al. 1995)

$$R_b = 2(Sc)^{2/3} (Pr)^{-2/3} (ku_*)^{-1} \quad (30)$$

where

$Sc$  = Schmidt number

$Pr$  = Prandtl number (= 0.72)

The Schmidt number is equal to 1 for O<sub>3</sub>, 0.76 for CO, 0.98 for NO<sub>2</sub>, and 1.15 for SO<sub>2</sub>.

## 2.7. Canopy resistance calculation for CO

### 2.7.1. In-leaf periods

As removal of CO by vegetation is not directly related to transpiration, the canopy resistance for CO in in-leaf

periods ( $R_{c,InLeaf}$ ) is set to a constant based on data from Bidwell and Fraser (1972).

$$R_{c,InLeaf} = 50,000 \quad (\text{sm}^{-1}) \quad (31)$$

### 2.7.2. Leaf-off Periods

The canopy resistance for CO in out-of-leaf periods ( $R_{c,OutLeaf}$ ) is set to a constant based on data from Bidwell and Fraser (1972).

$$R_{c,OutLeaf} = 1,000,000 \quad (\text{sm}^{-1}) \quad (32)$$

## 2.8. Canopy resistance calculation for NO<sub>2</sub>, O<sub>3</sub>, and SO<sub>2</sub>

### 2.8.1. In-leaf periods

The canopy resistances for NO<sub>2</sub>, O<sub>3</sub>, and SO<sub>2</sub> in in-leaf periods ( $R_{c,InLeaf}$ ) can be calculated as

$$\frac{1}{R_{c,InLeaf}} = \frac{1}{r_s + r_m} + \frac{1}{r_{soil}} + \frac{1}{r_t} \quad (33)$$

where

- $r_s$  = Stomatal resistance
- $r_m$  = Mesophyll resistance
- $r_{soil}$  = Soil resistance (= 2941 sm<sup>-1</sup>)
- $r_t$  = Cuticular resistance

Calculations of the stomatal resistance are described in detail in section 2.9.

The mesophyll resistance ( $r_m$ ) is calculated as

$$r_m = \frac{r_{baseM}}{LAI} \quad (34)$$

where

- $r_{baseM}$  = Base mesophyll resistance

The cuticular resistance ( $r_t$ ) is calculated as

$$r_t = \frac{r_{baseC} \times \frac{D_v}{D}}{2 \times LAI} \quad (35)$$

where

- $r_{baseC}$  = Base cuticular resistance
- $D_v$  = Water vapor diffusivity (= 24.9)
- $D$  = Diffusivity

$r_{baseM}$ ,  $r_{baseC}$ , and  $D$  used in the calculations of  $r_m$  and  $r_l$  for  $\text{NO}_2$ ,  $\text{O}_3$ , and  $\text{SO}_2$  are presented in Table 1.

Table 1 Parameter values

Parameter	$\text{NO}_2$	$\text{O}_3$	$\text{SO}_2$
$r_{baseM}$	600 ( $\text{s m}^{-1}$ ) (Lovett 1994)	60 ( $\text{s m}^{-1}$ ) (Hosker and Lindberg 1982)	0 ( $\text{s m}^{-1}$ ) (Wesely 1989)
$r_{baseC}$	20,000 ( $\text{s m}^{-1}$ ) (Wesely 1989)	10,000 ( $\text{s m}^{-1}$ ) (Lovett 1994)	8,000 ( $\text{s m}^{-1}$ ) (Lovett 1994)
$D$	15.6	15.3	13.2

### 2.8.2. Out-of-leaf periods

The canopy resistances for  $\text{NO}_2$ ,  $\text{O}_3$ , and  $\text{SO}_2$  in the out-of-leaf periods ( $R_{c,OutLeaf}$ ) can be linearly interpolated based on LAI of evergreen vegetation calculated for an urban area and default canopy resistances defined for evergreen LAI values (Table 2).

Table 2 Default canopy resistances for out-of-leaf periods

Evergreen LAI	Canopy Resistance for $\text{NO}_2$	Canopy Resistance for $\text{O}_3$	Canopy Resistance for $\text{SO}_2$
0.0	2941 ( $\text{s m}^{-1}$ )	2941 ( $\text{s m}^{-1}$ )	2941 ( $\text{s m}^{-1}$ )
0.1	2888	2840	2831
0.2	2837	2746	2729
0.3	2787	2658	2634
0.4	2740	2576	2545
0.5	2693	2498	2462
0.6	2649	2425	2384
0.7	2606	2357	2312
0.8	2564	2291	2243
0.9	2524	2230	2178
1.0	2484	2172	2117
1.5	2305	1920	1857
2.0	2150	1721	1654
2.5	2015	1560	1491
3.0	1896	1426	1357
3.5	1790	1313	1245
4.0	1695	1217	1151
4.5	1610	1134	1069
5.0	1533	1061	999

6.0	1399	941	882
7.0	1286	845	790
8.0	1190	767	715
9.0	1108	702	653
10.0	1036	647	601
11.0	973	600	557
12.0	917	560	519
13.0	868	525	486

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## 2.9. Stomatal resistance calculation

The visible part (400 – 700 nm) or photosynthetically active radiation (PAR) of the solar spectrum is largely absorbed to drive photosynthesis, while the near-infrared part (700 – 3000 nm) is largely scattered by vegetations (Norman 1982). Direct beam and sky diffuse radiation are intercepted very differently by canopies (Norman 1982). Diffuse radiation is used much more efficiently than direct radiation by a canopy of photosynthesizing leaves (Weiss and Norman 1985). The stomatal resistance is linked to leaf photosynthesis (Baldocchi 1994). Calculating canopy photosynthetic rates from leaf photosynthetic rates requires dividing the canopy into N layers, in which  $\Delta F$ , the leaf area index in each layer, usually chosen as 0.1 or 0.2 (Norman 1980). It is preferable to compute stomatal resistance on the basis of the irradiance on both sunlit and shaded leaves and weighting these resistances according to the fraction of sunlit and shaded leaf area (Baldocchi et al., 1987).

Therefore, derivation of stomatal conductance  $g_s$ , the inverse of stomatal resistance of a canopy involves these steps, which are explained in the following sections.

1. Divide solar radiation above the canopy into visible (PAR) and near-infrared portions (Section 2.9.1).
2. Divide PAR above the canopy into direct beam and diffuse radiation (Section 2.9.1).
3. Divide the canopy into N layers and calculate sunlit and shaded leaf areas in each layer of the canopy (Section 2.9.2).
4. Calculate flux density of PAR intercepted by sunlit and shaded leaves in each layer of the canopy (Section 2.9.3).
5. Calculate stomatal conductance for sunlit and shaded leaves in each layer of the canopy (Sections 2.9.4 and 2.9.5).
6. Weight stomatal conductance for each layer according to the fraction of sunlit and shaded leaf area (Section 2.9.6).
7. Accumulate stomatal conductance for sunlit and shaded leaves throughout all layers to derive stomatal conductance for the whole canopy (Section 2.9.7).

### 2.9.1. Visible and near-infrared, direct and diffuse components of solar incident

Weiss and Norman (1985) obtained equations to predict direct and diffuse components of solar irradiance in both the visible (PAR) and near-infrared wave bands from measurements of only the total incoming solar radiation. Direct visible component ( $R_{DV}$ ), diffuse visible component ( $R_{dV}$ ), direct near-infrared component ( $R_{DN}$ ), and diffuse near-infrared component ( $R_{dN}$ ) of the solar radiation can be approximated by (Weiss and Norman 1985):

$$R_{DV} = 600 \exp\left(-0.185 \times \frac{P}{P_0} \times m\right) \cos \theta \quad (36)$$

$$R_{dV} = 0.4(600 - R_{DV}) \cos \theta \quad (37)$$

$$R_{DN} = 720 \exp\left(-0.06 \frac{P}{P_0} m - w\right) \cos \theta \quad (38)$$

$$R_{dN} = 0.6(720 - R_{DN} - w) \cos \theta \quad (39)$$

where

- $E$  = Extinction coefficient (= 0.185)
- $P$  = Actual pressure (kPa)
- $P_0$  = Sea level pressure (= 101.325 kPa)
- $m$  = Optical air mass

With a flat approximation to the atmosphere,  $m$  can be defined as:

$$m = \frac{1}{\cos \theta} \quad (40)$$

- $\theta$  = Solar zenith angle
- $w$  = Water absorption in the near infrared for 10 mm of precipitable water

$w$  can be derived from

$$w = 1320 \text{anti log}_{10} \left[ -1.1950 + 0.4459 \log_{10} m - 0.0345 (\log_{10} m)^2 \right] \quad (41)$$

The fraction of the visible (or near-infrared) in the direct beam was estimated by analyzing the relationship between the fraction and the ratio of measured to potential total solar radiation, *RATIO* (Weiss and Norman 1985).

$$f_V = \frac{R_{DV}}{R_V} \left[ 1 - \left( \frac{A - \text{RATIO}}{B} \right)^{2/3} \right] \quad (42)$$

$$f_N = \frac{R_{DN}}{R_N} \left[ 1 - \left( \frac{C - \text{RATIO}}{D} \right)^{2/3} \right] \quad (43)$$

$$\text{RATIO} = \frac{R_T}{R_V + R_N} \quad (44)$$

where

$R_T$  = Measurement of total incoming solar radiation

$R_V = R_{DV} + R_{dV}$

$R_N = R_{DN} + R_{dN}$

$A$ ,  $B$ ,  $C$ , and  $D$  are 0.9, 0.7, 0.88, and 0.68, respectively.  $\text{RATIO}$  is never allowed to exceed  $A$  or  $C$ . If  $\text{RATIO}$  should exceed  $A$  or  $C$ , it is set equal to  $A$  or  $C$ .

It is assumed that 46% of the averaged hourly solar radiation is in the visible (Norman 1982). Norman (1982) states this percentage is essentially independent of zenith angle and cloudiness. Flux densities of direct and diffuse radiation of PAR on top of the canopy can be estimated as

$$\text{PAR}_{dir} = f_V \times (0.46R_T) \times F_c \quad (45)$$

$$\text{PAR}_{diff} = (1 - f_V) \times (0.46R_T) \times F_c \quad (46)$$

,where

$F_c$  = Conversion factor from  $\text{W m}^{-2}$  to  $\mu\text{E m}^{-2} \text{s}^{-1}$  (=4.6)

$F_c$  was derived by converting energy of solar irradiance into photosynthetic photon flux density (PPFD), which is a measure of the number of photons in the visible spectrum range falling on a  $1 \text{ m}^2$  area per second. PPFD is a measure of PAR. The energy carried by electromagnetic radiation is contained in the photons that travel as a wave. The energy in a photon varies with its frequency, according to the equation:

$$E = hv = \frac{hc}{\lambda}$$

$E$  = Energy (J)

$h$  = Plank's constant (=  $6.626 \times 10^{-34} \text{ J s}^{-1}$ )

$v$  = Frequency

$c$  = Speed of light (=  $3.0 \times 10^8 \text{ m s}^{-1}$ )

$\lambda$  = Wavelength (m)

The conversion is conducted based on the center wavelength (=550 nm) of the visible part of the spectrum. As one photon in a certain wavelength has the energy calculated by Eq. 4-xx, the number of photons in 550 nm comprising one joule (J) can be calculated as  $27.70 \times 10^{17}$ . This number can be converted into as  $4.59 \times 10^{-6}$  moles where one mole = Avogadro's number =  $6.02 \times 10^{23}$ . Watt (W) is a unit of power that measures rate of flow of energy. One (W)

is equivalent to one (J) of energy per second. Thus, one (W) of power from light at 550 nm would need to provide  $27.70 \times 10^{17}$  photons, or  $4.6 \times 10^{-6}$  moles per second. Another unit, Einstein (E) is introduced here, which is used in irradiance and in photochemistry. One einstein is defined as one mole of photons, regardless of their frequency. One (W) of power from light would need to provide  $4.6 \times 10^{-6}$  (E) or 4.6 ( $\mu\text{E}$ ) per second. Therefore, irradiance in  $\text{W m}^{-2}$  can be converted into PPFD in  $\mu\text{E m}^{-2} \text{s}^{-1}$  by multiplying 4.6.

### 2.9.2. Canopy layers and sunlit/shaded leaf area index for each layer

The canopy is divided into N layers, in which the leaf area index in each layer ( $\Delta F$ ) chosen as 0.1 or 0.2, to calculate the PAR on sunlit and shaded leaves separately, assuming a mean angle between the direction of the sun and the plane of sunlit leaves and the spherical leaf angle distribution. This procedure is based on methods explained in Norman (1980)

The direct beam transmittance below layer  $j$  of the canopy with a spherical leaf distribution is

$$T_{B,j} = \exp\left(-\frac{F_j}{2 \cos \theta}\right) \quad (47)$$

where

$$\begin{aligned} F_j &= \text{Leaf area index at the layer } j \\ \theta &= \text{Zenith angle of the sun} \end{aligned}$$

For a spherical leaf distribution, the sunlit leaf area index in the  $j^{\text{th}}$  layer is given by  $\Delta F_j^*$

$$\Delta F_j^* = (T_{B,j} - T_{B,j+1}) 2 \cos \theta \quad (48)$$

The fraction of leaf area in the  $j^{\text{th}}$  layer that is sunlit is given by

$$\frac{\Delta F_j^*}{\Delta F} \quad (49)$$

the shaded leaf area index in the  $j^{\text{th}}$  layer is given by

$$\Delta F - \Delta F_j^* \quad (50)$$

### 2.9.3. Flux density of PAR on sunlit/shaded leaves in each layer

Flux density of PAR on sunlit and shaded leaves can be estimated with methods outlined in Norman (1982) and Baldocchi et al. (1987). Shaded leaves receive only diffuse light. The flux density of diffuse PAR on shaded leaves in the  $j^{\text{th}}$  layer can be estimated as

$$PAR_{shade,j} = PAR_{diff} \exp(-0.5F^{0.7}) \times S_j + C_j \quad (51)$$

$$PAR_{diff} = \text{Flux density of diffuse PAR above the canopy}$$

$F$  = Leaf area index for whole canopy  
 $S_j$  = Scaling factor of diffuse flux density of PAR for the  $j^{\text{th}}$  layer

$$S_j = \frac{\exp\left(-0.5F \times \frac{j-0.5}{N}\right)}{\sum_{j=1}^N \exp\left(-0.5F \times \frac{j-0.5}{N}\right)} \quad (52)$$

C arises from multiple scattering of direct beam radiation and is given by

$$C_j = 0.07 PAR_{dir} \left[ 1.1 - 0.1 \left( F_j - \frac{\Delta F}{2} \right) \right] \exp(-\sin \beta) \quad (53)$$

Conceptually, the 0.07 represents a scattering coefficient, the term in brackets accounts for the decrease in multiple scattering with depth and the last exponential term accounts for the increased scattering at high zenith angles.

Sunlit leaves receive both direct and diffuse lights. The flux density of PAR on sunlit leaves in the  $j^{\text{th}}$  layer can be estimated as

$$PAR_{sun,j} = PAR_{dir} \frac{\cos \alpha}{\sin \beta} + PAR_{shade,j} \quad (54)$$

where

$PAR_{dir}$  = Flux density of direct PAR above the canopy  
 $\alpha$  = Angle between a leaf and the sun (= 60 degrees)  
 $\beta$  = Solar elevation angle

$PAR_{dir}/\cos\beta$  is the visible irradiance on a plane perpendicular to the direction of the sun.

#### 2.9.4. Stomatal conductance for sunlit/shaded leaves in each layer

This procedure is based on methods explained in Farquhar et al. (1980), Baldochi (1994), and Harley et al. (1992). Stomatal conductance  $g_s$  for each layer of the canopy can be computed as:

$$g_s = \frac{mArh}{C_s} + b' \quad (55)$$

where

$m$  = Dimensionless slope (= 10)  
 $A$  = Photosynthetic flux density of a leaf  
 $rh$  = Relative humidity  
 $b'$  = Zero intercept when A is equal to or less than zero (= 0.02 mol m<sup>-2</sup> s<sup>-1</sup>)  
 $C_s$  = Leaf surface CO<sub>2</sub> concentration

A is represented as:

$$A = V_c - 0.5V_o - R_d \quad (56)$$

where

- $V_c$  = Carboxylation rate of CO<sub>2</sub> exchange between leaf and atmosphere
- $V_o$  = Oxygenation rate of CO<sub>2</sub> exchange between leaf and atmosphere
- $R_d$  = Dark respiration rate of CO<sub>2</sub> exchange between leaf and atmosphere

The term  $V_c - 0.5V_o$  is expressed by Baldocchi (1994) as

$$V_c - 0.5V_o = \min(W_c, W_j) \left( 1 - \frac{\Gamma}{C_i} \right) \quad (57)$$

where

- $W_c$  = Carboxylation rate when ribulose biphosphate (RuBP) carboxylase/oxygenase is saturated
- $W_j$  = Carboxylation rate when RuBP regeneration is limited by electron transport
- $\min(W_c, W_j)$  = Minimum value between these two rate variables
- $\Gamma$  = CO<sub>2</sub> compensation point in the absence of dark respiration
- $C_i$  = Internal CO<sub>2</sub> concentration

Internal CO<sub>2</sub> concentration can be expressed as

$$C_i = C_s - \frac{A}{g_s} \quad (58)$$

Leaf surface CO<sub>2</sub> concentration,  $C_s$  can be expressed as

$$C_s = C_a - \frac{A}{g_b} \quad (59)$$

where

- $C_a$  = Atmosphere's CO<sub>2</sub> concentration (= 360 ppm)
- $g_b$  = Conductance across the laminar boundary layer of a leaf (mol m<sup>-2</sup> s<sup>-1</sup>) for CO<sub>2</sub> exchange

$$g_b = \frac{1}{R_a + R_{b,CO_2}} \quad (60)$$

Both,  $W_j$  and  $W_c$  take the algebraic form

$$V_c - 0.5V_o = \frac{aC_i - ad}{eC_i + b} \quad (61)$$

### 2.9.5. Derivation of photosynthetic flux density of a leaf

The goal is to derive an equation describing  $A$  that is independent of  $C_s$ ,  $C_i$ , and  $g_s$ , the term  $C_s$  is eliminated by inserting Equation 59 into Equations 58 and 55.

$$C_i = C_a - \frac{A}{g_b} - \frac{A}{g_s} \quad (62)$$

$$g_s = \frac{mArh}{C_a - \frac{A}{g_b}} + b' \quad (63)$$

The term,  $g_s$  is eliminated by inserting Equation 63 to Equation 62.

$$\begin{aligned} C_i &= C_a - \frac{A}{g_b} - \frac{A}{\frac{mArh}{C_a - \frac{A}{g_b}} + b'} = C_a - \frac{A}{g_b} - \frac{A \left( C_a - \frac{A}{g_b} \right)}{mArh + b' \left( C_a - \frac{A}{g_b} \right)} \\ &= \frac{C_a g_b \left[ mArh + b' \left( C_a - \frac{A}{g_b} \right) \right] - A \left[ mArh + b' \left( C_a - \frac{A}{g_b} \right) \right] - A g_b \left( C_a - \frac{A}{g_b} \right)}{g_b \left[ mArh + b' \left( C_a - \frac{A}{g_b} \right) \right]} \\ &= \frac{C_a g_b mArh + C_a^2 b' g_b - C_a b' A - m r h A^2 - A b' C_a + \frac{b' A^2}{g_b} - g_b A C_a + A^2}{g_b mArh + b' C_a g_b - b' A} \\ &= \frac{\left( 1 + \frac{b'}{g_b} - m r h \right) A^2 + C_a (g_b m r h - 2 b' - g_b) A + C_a^2 b' g_b}{(g_b m r h - b') A + b' C_a g_b} \\ &= \frac{\alpha A^2 + \beta A + \gamma}{\theta A + \frac{\gamma}{C_a}} \end{aligned} \quad (64)$$

$$\alpha = 1 + \frac{b'}{g_b} - m r h \quad (65)$$

$$\beta = C_a (g_b m r h - 2 b' - g_b) \quad (66)$$

$$\gamma = C_a^2 b' g_b \quad (67)$$

$$\theta = g_b m r h - b' \quad (68)$$

From Equations 56 and 61,

$$\begin{aligned} A + R_d &= \frac{aC_i - ad}{eC_i + b} \\ AeC_i + Ab + R_d eC_i + R_d b &= aC_i - ad \\ (Ae + R_d e - a)C_i &= -ad - R_d b - Ab \\ C_i &= \frac{-ad - R_d b - Ab}{Ae + R_d e - a} \end{aligned} \quad (69)$$

With Equations 64 and 69,

$$\begin{aligned} \frac{\alpha A^2 + \beta A + \gamma}{\theta A + \frac{\gamma}{C_a}} &= \frac{-ad - R_d b - Ab}{Ae + R_d e - a} \\ (\alpha A^2 + \beta A + \gamma)(Ae + R_d e - a) &= (-ad - R_d b - Ab) \left( \theta A + \frac{\gamma}{C_a} \right) \\ \therefore e\alpha A^3 + \alpha R_d e A^2 - a\alpha A^2 + e\beta A^2 + \beta R_d e A - a\beta A + e\gamma A + R_d e \gamma - a\gamma & \\ &= -ad\theta A - ad \frac{\gamma}{C_a} - R_d b \theta A - R_d b \frac{\gamma}{C_a} - b\theta A^2 - b \frac{\gamma}{C_a} A \\ \therefore e\alpha A^3 + (e\beta + b\theta - a\alpha + e\alpha R_d) A^2 + \left( e\gamma + b \frac{\gamma}{C_a} - a\beta + ad\theta + eR_d \beta + R_d b \theta \right) A & \\ &\quad - a\gamma + ad \frac{\gamma}{C_a} + eR_d \gamma + R_d b \frac{\gamma}{C_a} = 0 \\ \therefore A^3 + \frac{e\beta + b\theta - a\alpha + e\alpha R_d}{e\alpha} A^2 + \frac{e\gamma + b \frac{\gamma}{C_a} - a\beta + ad\theta + eR_d \beta + R_d b \theta}{e\alpha} A & \\ &\quad + \frac{-a\gamma + ad \frac{\gamma}{C_a} + eR_d \gamma + R_d b \frac{\gamma}{C_a}}{e\alpha} = 0 \end{aligned} \quad (70)$$

The solution of the cubic equation is taken from Press et al. (1989). If Equation 70 is manipulated into the form

$$x^3 + px^2 + qx + r = 0, \quad (71)$$

where

$$\begin{aligned}
 p &= \frac{e\beta + b\theta - a\alpha + e\alpha R_d}{e\alpha} \\
 q &= \frac{e\gamma + b\frac{\gamma}{C_a} - a\beta + ad\theta + eR_d\beta + R_db\theta}{e\alpha} \\
 r &= \frac{-a\gamma + ad\frac{\gamma}{C_a} + eR_d\gamma + R_db\frac{\gamma}{C_a}}{e\alpha}
 \end{aligned} \tag{72}$$

three roots for the cubic equation are

$$x_1 = -2\sqrt{Q} \cos\left(\frac{\theta}{3}\right) - \frac{p}{3} \tag{73}$$

$$x_2 = -2\sqrt{Q} \cos\left(\frac{\theta + 2\pi}{3}\right) - \frac{p}{3} \tag{74}$$

$$x_3 = -2\sqrt{Q} \cos\left(\frac{\theta + 4\pi}{3}\right) - \frac{p}{3} \tag{75}$$

where

$$Q = \frac{p^2 - 3q}{9} \tag{76}$$

$$R = \frac{2p^3 - 9pq + 27r}{54} \tag{77}$$

$$\theta = a \cos\left(\frac{R}{\sqrt{Q^3}}\right) \tag{78}$$

The photosynthetic flux density of a leaf ( $A$ ) corresponds to root number three ( $x_3$ ). The variables  $a$ ,  $b$ ,  $d$ , and  $e$  are coefficient from Equation 61. If  $W_c$  is minimal, these coefficients correspond to

$$W_c = V_c - 0.5V_o = \frac{aC_i - ad}{eC_i + b} = \frac{V_{c\max}(C_i - \Gamma)}{C_i + K_c\left(1 + \frac{[O_2]}{K_o}\right)} \tag{79}$$

where

- $V_{c\max}$  = Maximum carboxylation rate when RuBP carboxylase/oxygenase is saturated
- $K_c$  = Michaelis-Menten coefficients for  $CO_2$  (= 333 microbars at 25 °C)
- $K_o$  = Michaelis-Menten coefficients for  $O_2$  (= 295 millibars at 25 °C)

- $\Gamma$  = CO<sub>2</sub> compensatio point in the absence of dark respiration  
 $[O_2]$  = Partial pressures of O<sub>2</sub> in the intercellular air space (= 210 μmol/mol)

The temperature dependencies of the  $K_c$  and  $K_o$  can be compensated for with Arrhenius Equation (Farquhar et al. 1980);

$$K_c = K_c(25^\circ C) \exp\left[\frac{(T - 298)E}{298RT}\right] \quad (80)$$

$$K_o = K_o(25^\circ C) \exp\left[\frac{(T - 298)E}{298RT}\right] \quad (81)$$

where

- $E$  = Relevant activation energy  
 $R$  = Universal gas constant  
 $T$  = Absolute leaf temperature

If  $W_j$  is minimal,  $a$ ,  $b$ ,  $d$ , and  $e$  coefficients correspond to

$$W_j = V_c - 0.5V_o = \frac{aC_i - ad}{eC_i + b} = \frac{J(C_i - \Gamma)}{4C_i + 8\Gamma} \quad (82)$$

where  $J$  is the potential rate of electron transport and expressed as (Harley et al. 1992):  
 for sunlit leaves in the  $j^{th}$  layer of the canopy

$$J = \frac{\alpha PAR_{sun,j}}{\sqrt{1 + \frac{\alpha^2 PAR_{sun,j}^2}{J_{max}^2}}} \quad (83)$$

and, for shaded leaves in the  $j^{th}$  layer of the canopy

$$J = \frac{\alpha PAR_{shade,j}}{\sqrt{1 + \frac{\alpha^2 PAR_{shade,j}^2}{J_{max}^2}}} \quad (84)$$

where

- $\alpha$  = Efficiency of light energy conversion on an incident light basis (= 0.055 mol electrons/mol photons)  
 $PAR_{sun,j}$  = Flux density of PAR on sunlit leaves in the  $j^{th}$  layer of canopy  
 $PAR_{shade,j}$  = Flux density of PAR on shaded leaves in the  $j^{th}$  layer of canopy  
 $J_{max}$  = Light-saturated rate of electron transport (= 171 at 25 °C for trees)

The temperature dependencies of the  $J_{max}$  can be compensated for with Arrhenius Equation (Farquhar et al. 1980);

$$J_{\max} = J_{\max}(25^{\circ}\text{C}) \exp\left[\frac{(T - 298)E}{298RT}\right] \quad (85)$$

where

- $E$  = Relevant activation energy
- $R$  = Universal gas constant
- $T$  = Absolute leaf temperature

### 2.9.6. Weighted stomatal conductance for each layer

According to Norman (1982), stomatal conductance for sunlit and shaded leaves in a layer of the canopy can be weighted with sunlit and shaded leaf area index for that layer to estimate the stomatal conductance for that layer.

$$g_{s,j} = \Delta F_j^* g_{s,\text{sun},j} + (\Delta F - \Delta F_j^*) g_{s,\text{shade},j} \quad (86)$$

### 2.9.7. Stomatal conductance for whole layers

Stomatal conductance for the whole layers can be calculating by taking summation of the stomatal conductance for each layer. Stomatal resistance is a reciprocal of stomatal conductance.

$$g_s = \sum_{j=1}^N g_{s,j} \quad (87)$$

### 2.10. Transpiration flux calculation

Transpiration is the escape of water vapor from plants as controlled to a considerable degree by leaf resistances. The process is comprised of two stages: evaporation of water from cell walls and diffusion out of the leaf mainly through stomata (Kramer 1983). Transpiration flux,  $T_f$  ( $\text{g m}^{-2} \text{hr}^{-1}$ ) is estimated as (Kramer 1983):

$$T_f = \frac{C_{\text{leaf}} - C_{\text{air}}}{\frac{1}{g_s} + R_a} \cdot \frac{3600}{LAI} \quad (88)$$

where

- $C_{\text{leaf}}$  = Water vapor concentration at the evaporating surfaces within the leaf ( $\text{g m}^{-3}$ )
- $C_{\text{air}}$  = Water vapor concentration in the air ( $\text{g m}^{-3}$ )
- $g_s$  = Stomatal conductance ( $\text{s m}^{-1}$ )
- $R_a$  = Aerodynamic resistance ( $\text{s m}^{-1}$ )
- $LAI$  = Leaf area index

$C_{leaf}$  and  $C_{air}$  are calculated as (Monteith and Unsworth 1990):

$$C_{leaf} = \frac{M_w e_s}{RT} = \frac{2165 e_s}{T} \quad (89)$$

$$C_{air} = \frac{M_w e}{RT} = \frac{2165 e}{T} \quad (89)$$

$M_w$  = Molecular weight of water (=18 g mol<sup>-1</sup>=18000 g kmol<sup>-1</sup>)

$R$  = Universal gas constant (=8.314 J mol<sup>-1</sup> K<sup>-1</sup>)=8.314 kPa m<sup>-3</sup> kmol<sup>-1</sup> K<sup>-1</sup>)

$e_s$  = Saturation vapor pressure (kPa)

$e$  = Vapor pressure (kPa)

$T$  = Temperature (K)

### 2.11. 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:

$$I_{unit} = \frac{F}{F + M_{total}} \cdot 100 \quad (90)$$

where

$F$  = Pollutant flux (g m<sup>-2</sup> h<sup>-1</sup>)

$M_{total}$  = Total air pollutant mass per unit tree cover (g m<sup>-2</sup>)

$$M_{total} = H \cdot C \quad (91)$$

where

$H$  = Urban mixing height (m)

$C$  = Air pollutant concentration (g m<sup>-3</sup>)

Hourly air quality improvement for total tree cover,  $I_{total}$  (%) is calculated as:

$$I_{total} = I_{unit} \cdot \frac{T_c}{100} \quad (92)$$

where

$T_c$  = Total tree cover in the city (%)

### 2.12. Monetary value calculation

Monetary value of pollution removal by trees is estimated using the median externality values for the United States for each pollutant. The externality values are: CO=\$950t<sup>-1</sup>, NO<sub>2</sub>=\$6750t<sup>-1</sup>, PM10=\$4500t<sup>-1</sup>, SO<sub>2</sub>=\$1650t<sup>-1</sup> (Murray

et al. 1994). Externality value for O<sub>3</sub> was set to equal the value for NO<sub>2</sub>.

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