Environmental Pollution 215 (2016) 48–57

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Comprehensive national database of tree effects on air quality and human health in the United States☆

Satoshi Hirabayashi [a, *], David J. Nowak [b]

[a] The Davey Institute, The Davey Tree Expert Company, 5 Moon Library, State University of New York, Syracuse, NY 13210, United States
[b] USDA Forest Service, 5 Moon Library, State University of New York, Syracuse, NY 13210, United States

ARTICLE INFO

Article history:
Received 12 November 2015
Received in revised form
4 April 2016
Accepted 19 April 2016

Keywords:
Air quality
Dry deposition
Human health
National database
Forest

ABSTRACT

Trees remove air pollutants through dry deposition processes depending upon forest structure, meteorology, and air quality that vary across space and time. Employing nationally available forest, weather, air pollution and human population data for 2010, computer simulations were performed for deciduous and evergreen trees with varying leaf area index for rural and urban areas in every county in the conterminous United States. The results populated a national database of annual air pollutant removal, concentration changes, and reductions in adverse health incidences and costs for NO_2, O_3, $PM_{2.5}$ and SO_2. The developed database enabled a first order approximation of air quality and associated human health benefits provided by trees with any forest configurations anywhere in the conterminous United States over time.

Comprehensive national database of tree effects on air quality and human health in the United States was developed.

1. Introduction

Air pollution is responsible for many adverse effects on human health and well-being. In the United States, it is estimated that 4700 and 130,000 deaths annually are attributable to ground-level ozone (O_3) and fine particulate matter ($PM_{2.5}$), respectively in 2005 (Fann et al., 2012). The World Health Organization estimated that 800,000 deaths annually could be attributed to urban air pollutants worldwide (WHO, 2002). Under provisions of the Clean Air Act, the United States Environmental Protection Agency (EPA) established National Ambient Air Quality Standards (NAAQS) for six criteria air pollutants (CAP) to improve the quality of air in the United States (US EPA, 2015a). The CAP includes carbon monoxide (CO), nitrogen dioxide (NO_2), ground-level ozone (O_3), sulfur dioxide (SO_2), and particulate matter consisting of particles smaller than 10 and 2.5 µm (PM_{10} and $PM_{2.5}$).

Air pollutants can be removed through primarily three mechanisms: chemical reactions, wet deposition, and dry deposition (Rasmussen et al., 1975; Fowler, 1980). Chemical reactions in a gas phase can result in aerosols in the atmosphere that are removed through wet or dry deposition processes, or produce oxidized products such as carbon dioxide (CO_2) and water vapor (Nowak, 1994). Deposition is a process by which gaseous and particulate pollutants are transferred to the terrestrial surfaces such as soils, vegetation canopies, and man-made structures as well as marine surfaces of the Earth; wet deposition is caused by precipitation, while dry deposition is caused by air flows. Due to their large surface areas, trees play an important role in dry deposition processes. Gaseous pollutants are essentially deposited to trees through the leaf stomata, while particulate matters deposited to trees' surface (Fowler, 1980; Murphy and Sigmon, 1990; Smith, 1990). Trees and forests are increasingly employed as ecological engineering designs to biologically filter the air pollutants and improve air quality (Beckett et al., 1998). Besides controlling emission sources of air pollutants such as motor vehicles and energy plants, it is of interest to planners and managers to employ this approach to effectively improve health and well-being of human populations.

Pollution removal through dry deposition varies throughout a

☆ This paper has been recommended for acceptance by Elena Paoletti.

* Corresponding author.
E-mail addresses: satoshi.hirabayashi@davey.com (S. Hirabayashi), dnowak@fe.fed.us (D.J. Nowak).

http://dx.doi.org/10.1016/j.envpol.2016.04.068
0269-7491/

landscape, depending on forest structures, pollutant concentration, length of growing season, and meteorological variables, so does its effect to the local air quality and associated human health. The annual pollution removal and associated human health effects were quantified across the United States (Nowak et al., 2014). In their study, four air pollutants, NO_2, O_3, $PM_{2.5}$ and SO_2 were assessed to derive dry deposition by trees and link the results to reductions in human health incidences and costs for rural and urban areas within each county across the conterminous United States. This was the first to assess the air quality improvement provided by trees and associated human health effects for such a broad scale and coverage. However, for planners and managers in smaller municipality these analyses need to be done at a finer spatial resolution, which would take too much time and effort as the number of such areas is huge e.g., the number of census places and county subdivisions across the United States is over 41,000 (US Census Bureau, 2015). In addition, since the forest structures such as leaf area index, LAI (m^2 leaf area per m^2 projected ground area of canopy) and deciduous/evergreen species compositions in the municipalities will change through time due to tree growth, mortality, new plantings and/or natural regeneration, the results from one year are not applicable to another year in the future or past.

In this study, a new national database of air pollutant removal, concentration changes, and associated health incidence and cost reductions at the county level was developed to account for changes in the forest structure. A new solution is then proposed to downscale the county level analyses to the finer scale within counties based on the records in the newly developed database.

2. Methods

For 3094 rural and 2425 urban areas in counties in the conterminous United States delimited using 2010 Census data (US Census Bureau, 2015), deciduous and evergreen trees with varying LAI were separately employed in the national run of i-Tree Eco (i-Tree, 2015)'s dry deposition and human benefit models for 2010. i-Tree Eco is a component of i-Tree tools developed by the USDA Forest Service, in which US EPA's BenMAP (US EPA, 2015b) was incorporated to link air quality improvement to human health improvement (Nowak et al., 2014). Three analyses were conducted: 1) the total tree cover and leaf area index, 2) the flux to and from leaves and resultant changes in concentration for the four air pollutants, and 3) the reduction of adverse health incidences and costs due to changes in air pollutant concentration. To efficiently run the models for the entire areas, a batch processing was constructed.

2.1. Tree cover and leaf area index

Tree cover within each of urban and rural areas in the counties was derived from 2001 National Land Cover Database (NLCD) 30-m resolution tree cover maps (MRLC, 2015) and adjusted for its potential underestimates based on the methods detailed in Nowak and Greenfield (2012). It was assumed that the entire tree cover was either deciduous or evergreen, and the maximum (mid-summer) LAI values (LAI_{max}) varying within a typical range for boreal, temperate, and tropical forests (0–18) (Barbour et al., 1980; Scurlock et al., 2001) with 0.5 increments. For evergreen tree cover, LAI value was assumed to be constant at the mid-summer value throughout a year, whereas the minimum (mid-winter) LAI (LAI_{min}) was assumed to be 0 for deciduous tree cover. Deciduous trees had a four-week leaf transition period from leaf-off to leaf-on and vice versa based on the local spring leaf-on and autumn leaf-off dates determined from local frost free dates (NCDC, 2015a). A modified sigmoid function was used to estimate daily LAI values (LAI_{daily}) for the deciduous cover in each county during this four week period (Koller and Upadhyay, 2005; Wang et al., 2008):

$$LAI_{daily} = \frac{LAI_{max} - LAI_{min}}{1 + e^{-0.37(day_a - day_b)}} + LAI_{min} \tag{1}$$

where day_a is day of year and day_b is leaf-on date for spring, while day_a is leaf-off date and day_b is day of year for autumn.

2.2. Air pollutant removal and concentration change

Hourly pollutant flux per unit tree cover, F ($\mu g\ m^{-2}\ h^{-1}$) was estimated as a product of the dry deposition velocity, V_d ($m\ h^{-1}$), and the air pollutant concentration, C ($\mu g\ m^{-3}$):

$$F = V_d \cdot C \tag{2}$$

V_d for NO_2, O_3 and SO_2 were estimated as the inverse of the sum of resistances to pollutant transport in the crown space (r_a: aerodynamic resistance), adjacent to canopy surfaces (r_b: quasi-laminar boundary layer resistance), and on leaf surfaces (r_c: canopy resistance) (Baldocchi et al., 1987). Both r_a and r_b are a function of meteorological conditions including temperature, wind speed, solar angle, and cloud cover. r_c is calculated based on trees' biophysical variables including LAI and meteorological variables including temperature, pressure, relative humidity, and solar radiation. The detailed process is described in Hirabayashi et al. (2011, 2015). V_d for $PM_{2.5}$ for unit LAI was estimated based on the median of deposition velocity measurements for varied wind speeds reported in the literature. V_d was then multiplied by LAI, and F for $PM_{2.5}$ was computed accounting for the resuspension of the particles from leaves to the atmosphere due to the wind and wash-off of particles from leaves to the ground by precipitation. The detailed process for $PM_{2.5}$ dry depositions is given in Nowak et al. (2013). Annual air pollutant removal, R_a (t) can be calculated as

$$R_a = F_a \cdot TC \cdot A \tag{3}$$

where F_a ($t\ m^{-2}\ yr^{-1}$) is annual sum of F, TC (%) is tree cover percent and A (m^2) is area for the study area.

For each urban or rural area, hourly air quality improvement, I was calculated as the ratio between the mass of air pollutant removed within the tree cover area and the mass of air pollutant existed within the study area:

$$I = \frac{F \cdot TC \cdot A}{F \cdot TC \cdot A + C \cdot H \cdot A} \tag{4}$$

where H (m) is mixing height. Hourly concentration change, ΔC was estimated as:

$$\Delta C = \frac{C}{1 - I} - C \tag{5}$$

In BenMAP, seven concentration change metrics annually averaged from ΔC were employed; daily 1 h maximum of ΔC (1Max), daily mean of ΔC for 8–10 a.m. (3Mean), daily mean of ΔC for 6–9 am (4Mean), daily maximum of ΔC for 8 h moving average (8Max), daily mean of ΔC for 9 a.m.–4 p.m. (8Mean), daily mean of ΔC (24Mean), and quarterly mean of daily mean of ΔC (24MeanQ).

Hourly meteorological data for 2010 from 910 weather stations nationwide were employed from National Climatic Data Center weather stations (NCDC, 2015b). Hourly air pollutant concentration data for 2010 were obtained from the US EPA's Air Quality System (AQS) national database (US EPA, 2015c). The number of monitors ranged from 399 for NO_2 to 1232 for O_3. Upper air temperature and pressure for 2010 from 74 stations nationwide were obtained from National Oceanic and Atmospheric Administration Earth System

Research Laboratory (NOAA ESRL)'s radiosonde database (NOAA, 2015) to calculate hourly mixing height with US EPA's PCRAMMET program (US EPA, 1995) integrated into i-Tree Eco. These monitor stations are more densely located in urban than rural areas. The monitor located nearest to the geographic center for each of rural and urban areas was used to represent each area. Due to the scarcity of the monitors, more than 80% of both rural and urban areas were assigned monitors located outside of its boundary.

2.3. Adverse health incidence and cost

Adverse health effect categories analyzed include Acute Respiratory Symptoms (ARS), Emergency Room Visits (ERV), and Hospital Admissions, Respiratory (HAR) associated with NO_2, O_3, $PM_{2.5}$, and SO_2, Asthma Exacerbations (AE) associated with NO_2, $PM_{2.5}$, and SO_2, Mortality (M) associated with O_3 and $PM_{2.5}$, Acute/Chronic Bronchitis (AB/CB), Acute Myocardial Infarction (AMI), Hospital Admissions, Cardiovascular (HAC), Upper/Lower Respiratory Symptoms (URS/LRS), and Work Loss Days (WLD) associated with $PM_{2.5}$, and School Loss Days (SLD) associated with O_3.

BenMAP uses concentration-response functions that relate the concentration change metrics to changes in adverse health incidences for age group populations at the county level in the conterminous United States. Valuation functions are then used to convert the incidence changes to monetary values. Derived from BenMAP, i-Tree Eco holds multipliers for adverse health incidences and values per unit concentration change and per person in age groups for each county in the conterminous United States. Table 1 presents the value multipliers averaged for each health effect category across the counties. AE, CB and M multipliers were comparable to the values in the same category in the Air Quality Benefits Assessment Tool (AQBAT) of Canada (Judek et al., 2006). Due to the difference in health expenditure per capita between United States and Canada ($US 8233 vs. $US 4445) (Kane, 2012), the values for the United States were generally higher than Canada.

Multiplying the concentration change metrics estimated for rural/urban areas and population for the age group by the multipliers, tree effects on incidence and value for each health category were estimated. Most of the health effect categories had multiple functions corresponding to different air quality metrics and age groups; multiple estimates for a health effect category were aggregated by either averaging or summing the estimates. For instance, incidence estimates for HAR associated with NO_2 derived from three concentration-response functions for age groups 0–14, 15–64, and 65–99 were summed to produce an incidence change for the entire ages of 0–99:

$$I_{HAR,NO_2} = IM_{58} \cdot P_{0-14} \cdot 1Max + IM_{59} \cdot P_{15-64} \cdot 1Max + IM_{64} \cdot P_{65-99} \cdot 24Mean \quad (6)$$

where IM is incidence multiplier and the subscripts indicate the function number, P is population for age group denoted by the subscripts. For health effect values, value multipliers were used in Eqn. (6).

2.4. Batch processing and database creation

i-Tree Eco's dry deposition and BenMAP valuation models estimate hourly air quality and health benefits for NO_2, O_3, $PM_{2.5}$ and SO_2 for a study area with a defined tree cover, mid-summer LAI, and evergreen percentage, and then summarize the result for a year. This study required these models to run for deciduous (0% evergreen) and evergreen (100% evergreen) forest configurations separately with 37 LAI values for totally 5519 rural/urban areas, totaled over 400,000 iterations. To efficiently run the entire process, a batch process was constructed, in which a single run handles a unique combination of LAI, deciduous or evergreen trees, and urban or rural area in each county where nearest weather, radiosonde, air pollutant monitor stations were pre-assigned. The estimated air pollutant removal, concentration change metrics, change in health incidences and costs along with A (m^2) and TC (%) for all combinations of counties, rural/urban areas, air pollutants, leaf types, and LAIs were stored in a database.

2.5. Downscaling of air pollutant removal

Due to scarcity of weather, radiosonde and air pollutant monitor stations, monitors used to represent the rural or urban areas of a county may be representative for a smaller scale area such as place within the county. If this is the case, F_a in Eqn. (3) is the same for the county and the place for the same LAI. Therefore, looking up the newly developed database, for a place in rural or urban part of a county, annual air pollutant removal can be estimated by F_a for the county multiplied by the tree cover area for the place. The estimate can be made for each of deciduous and evergreen tree cover and the results can be weighted based on the deciduous and evergreen composition for the place.

2.6. Downscaling of air pollutant concentration change

Based on Eqn. (4), the ratio of hourly air quality improvement between a county, I_c and a place within the county, I_p is:

Table 1
Mean monetary value per incidence multiplier for health effect calculation.

Health effect	Air pollutant	Value ($)/Incidence
Acute Bronchitis (AE)	$PM_{2.5}$	88
Acute Myocardial Infarction (AMI)	$PM_{2.5}$	89,765
Acute Respiratory Symptoms (ARS)	NO_2, O_3, $PM_{2.5}$, SO_2	66
Asthma Exacerbation (AE)	NO_2, $PM_{2.5}$,SO_2	82
Chronic Bronchitis (CB)	$PM_{2.5}$	279,574
Emergency Room Visits, Respiratory (ERV)	NO_2, O_3, $PM_{2.5}$, SO_2	416
Hospital Admissions, Cardiovascular (HAC)	$PM_{2.5}$	38,302
Hospital Admissions, Respiratory (HAR)	NO_2, O_3, $PM_{2.5}$, SO_2	29,875
Lower Respiratory Symptoms (LRS)	$PM_{2.5}$	52
Mortality (M)	O_3, $PM_{2.5}$	7,773,554
School Loss Days (SLD)	O_3	98
Upper Respiratory Symptoms (URS)	$PM_{2.5}$	45
Work Loss Days (WLD)	$PM_{2.5}$	137

$$\frac{I_c}{I_p} = \frac{F \cdot TC_c \cdot A_c}{F \cdot TC_c \cdot A_c + C \cdot H \cdot A_c} \Big/ \frac{F \cdot TC_p \cdot A_p}{F \cdot TC_p \cdot A_p + C \cdot H \cdot A_p} = \frac{TC_c}{TC_p} \cdot \frac{TC_p + C \cdot H/F}{TC_c + C \cdot H/F} \quad (7)$$

where subscripts c and p denote parameters for county and place within the county, respectively. Assuming that the monitors for the county and the place are the same, F, C, and H remain the same for the same LAI. Since tree cover percent for the county and the place, TC_c and TC_p are from 0 to 1, C·H/F is usually much greater than TC_c and TC_p, and thus Eqn. (7) can be reduced to:

$$I_p \approx I_c \cdot \frac{TC_p}{TC_c} \quad (8)$$

As hourly ΔC and the seven concentration change metrics for the place are calculated based on I_p, they can be estimated from the county value multiplied with TC_p/TC_c.

Once the concentration change metrics for the place are estimated, the BenMAP protocol can be applied using the county-level incidence and value multipliers and age group populations for the place as shown in Eqn. (6).

3. Results and discussions

3.1. Tree cover

On average, rural had 40 times greater tree cover area than urban areas (81,000 vs. and 4000 (ha)). Average tree cover percent was 42% for rural and 31% for urban areas.

3.2. Air pollutant removal and concentration change

In urban areas, annual mean air pollutant concentration, C_a were 15.5 ($\mu g\ m^{-3}$) for NO_2, 61.7 ($\mu g\ m^{-3}$) for O_3, 10.0 ($\mu g\ m^{-3}$) for $PM_{2.5}$, and 4.9 ($\mu g\ m^{-3}$) for SO_2. C_a for rural areas were slightly smaller than urban areas. NO_2 and SO_2 are primary air pollutant, $PM_{2.5}$ is emitted directly from mobile sources and also created by secondary formation (Hodan and Barnard, 2004), and O_3 is a secondary pollutant. Primary air pollutant concentrations are typically higher near the emission sources, such as urban areas with a high volume of motor vehicle traffic and stationary industrial sources (Gualtieri and Tartaglia, 1998; Jenson, 1998). O_3 and secondary $PM_{2.5}$ are less impacted by local sources (Ito et al., 2005; Sarnat et al., 2010). Wind carries precursors of O_3 and $PM_{2.5}$ hundreds of miles away from their original source, which may smooth the variation across space.

Distributions of R_a and 1Max for all combinations of the air pollutant, rural or urban area, deciduous or evergreen trees, and LAI are presented as boxplots (Fig. 1). R_a, 1Max and other concentration change metrics were generally greater in rural than urban areas due to greater tree covers in rural areas. R_a and concentration change metrics for evergreen were always larger than deciduous trees in both rural and urban areas since LAI was assumed to be 0 in the winter for deciduous trees, resulting 0 pollutant removal and concentration change, while LAI was assumed to be constant throughout a year for evergreen trees. Due to the largest concentration across the country, O_3 generally had the highest removal and concentration changes among the four pollutants.

Both R_a and concentration changes increased as the LAI increased for each combination of the air pollutant, rural or urban area, and deciduous or evergreen trees. But the relationship is non-linear for NO_2, O_3 and SO_2; the magnitude of increase became smaller as LAI exceeded a threshold value around 5 (Fig. 2). This results agreed with the sensitivity of V_d to LAI (Hirabayashi et al., 2011). On the other hand, $PM_{2.5}$ removal and concentration changes were almost linearly increased with LAI since V_d for $PM_{2.5}$ was proportional to LAI. (Nowak et al., 2013).

By fixing the LAI value to 5 that is near the threshold (Fig. 2), sensitivity of F_a, R_a, and concentration change metrics to their input parameters in Eqns. (2)–(4), respectively were analyzed using the results for evergreen trees for totally 5519 rural and urban areas. For the four air pollutants, F_a was dependent on C_a as Pearson product moment correlation coefficient (PMCC), which is a simple measure of the dependence and linear relationship between two sets of values (Saltelli et al., 2000), between F_a and C_a ranged from 0.68 for $PM_{2.5}$ to 0.98 for NO_2., indicating near linear relationship. F_a had a limited dependence on V_d as PMCC was smaller than 0.05 for all air pollutants except for O_3 (PMCC was 0.43). TC (%) × A (m^2) or tree cover area (m^2) had a greater impact on R_a than F_a, and PMCC ranged from 0.55 for SO_2 to 0.97 for O_3.

Linearity between the seven concentration change metrics for O_3 and TC (%) was highest with PMCC of over 0.84. The concentration change metrics for NO_2 and $PM_{2.5}$ were also near linear with TC (%) as PMCC ranged from 0.57 to 0.70. For SO_2 though, PMCC between the concentration change metrics and TC (%) was slightly smaller, and F_a and C_a had a greater impact with PMCC of over 0.7.

3.3. Adverse health incidence and cost

Population and population density were larger for urban than rural areas; urban areas had 5 times larger population (102,000 vs. 19,000) and 46 times larger population density (690 vs. 15 (people km^{-2})) than rural areas. Because of the larger populations in urban areas, the relative smallness in air quality benefits for urban areas was offset in the health benefits; both reductions in adverse health incidence and cost were greater for urban than rural areas (Fig. 3). Same as air pollutant effects, evergreen trees were always better than deciduous trees in both rural and urban areas. Due to the greatest removal and concentration change for O_3, the avoided incidences were also greatest for O_3. Among the adverse health effects, incidence reductions for ARS associated with O_3 and $PM_{2.5}$, AE associated with NO_2 and $PM_{2.5}$, and SLD associated with O_3 were generally greatest, while costs reduction was greatest for O_3 and $PM_{2.5}$ because the changes in these pollutant concentrations were related to human mortality, which was assigned the greatest monetary values per incidence by BenMAP (Table 1).

Similar to air pollutant results, health effect results were increased as the LAI values increased non-linearly for NO_2, O_3 and SO_2, whereas almost linearly for $PM_{2.5}$. Fixing LAI to 5 for evergreen trees in both rural and urban areas, population had the highest PMCC with incidences and costs, ranging from 0.58 for HAR associated with SO_2 to 0.90 for AE associated with NO_2, indicating a near linear relationship between number of incidence and cost reductions and population.

3.4. Developed database

The developed national database is populated with annual removal and seven different concentration change metrics for NO_2, O_3, $PM_{2.5}$ and SO_2 as well as 25 health incidence and cost changes for all combinations of county, rural/urban areas, leaf type and LAI values, totaling to over 33 million values. Table 2 presents an example of the contents that present results for Onondaga County, NY for LAI of 5. These results represent general tendencies in the comparison of the estimates between rural/urban areas, deciduous/evergreen trees, and among the four air pollutants mentioned in the previous sections.

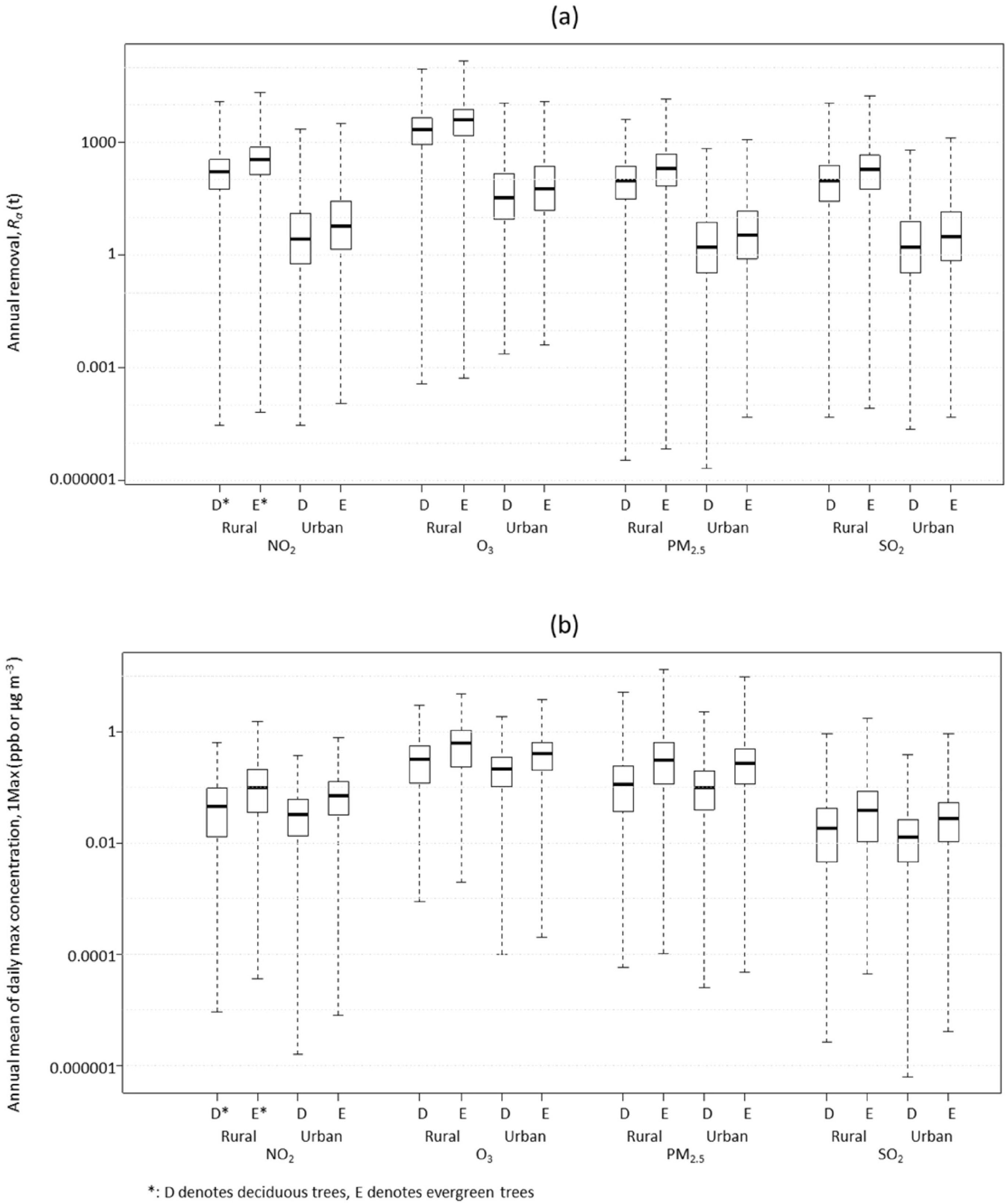

Fig. 1. Distribution of (a) annual air pollutant removal, R_a and (b) annual mean of daily maximum concentration, 1Max (unit is ppb for NO_2, O_3, and SO_2, and µg m^{-3} for $PM_{2.5}$) across the entire study area for LAI of 0 to 18.

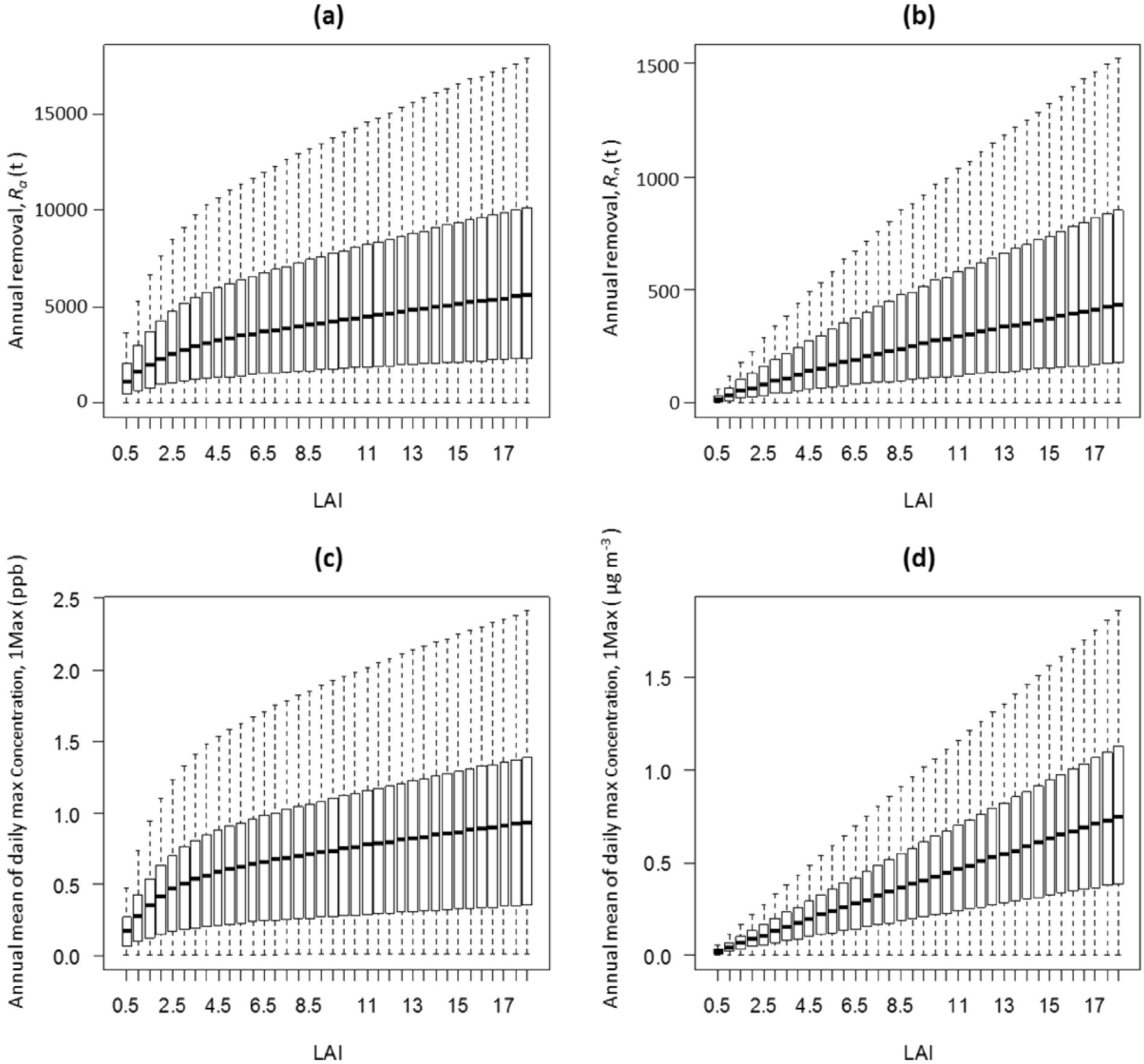

Fig. 2. Distribution of a) annual removal, R_a for O_3, b) annual removal, R_a for $PM_{2.5}$, c) annual mean of daily maximum concentration, 1Max for O_3, and d) annual mean of daily maximum concentration, 1Max for $PM_{2.5}$ against LAI for evergreen trees in rural areas.

3.5. Downscaled estimates

To demonstrate the usefulness of the developed database, annual air quality and health benefits provided by trees with 26.9% tree cover, 16.3% evergreen trees, and LAI of 5 were estimated for Syracuse, NY, which is in the urban area of Onondaga County. Table 3 presents the results for Syracuse estimated based on the urban area values in Table 2. Downscaling the county results to Syracuse produced first order approximations that agreed relatively well with the results for Syracuse estimated hourly and summarized annually by i-Tree Eco with generally less than 20% errors.

3.6. Limitations and advantages

There are several limitations in this study, associated with the national implementation of the models and the models themselves. Due to the limited number of the nationally available weather, radiosonde, and air pollutant monitor stations, the nearest monitors assigned may not represent the true values for the area. Rural areas where the nearest urban air pollutant monitors was assigned may overestimate the air pollutant concentration, resulting in the overestimated F_a. Although this study overcame the limitation of the previous work by Nowak et al. (2014) in which the forest structure was assumed to be constant across the area when the developed database is used to assess trees' effects in a smaller scale, the assumption of the constant weather and air quality conditions across the different scales remains.

The dry deposition model focused only on air pollutant removal by trees and did not include other indirect effects of trees on air quality, such as effects to building energy use (Heisler, 1986) and consequent emissions from power plants, air temperature reduction that leads to reduction of emissions from anthropogenic sources (Cardelino and Chameides, 1990), and biogenic emission of volatile organic compounds (VOCs) that are precursors to O_3 and $PM_{2.5}$ formation (Chameides et al., 1988; Hodan and Barnard, 2004). Various factors such as drought or other environmental stressors that affect tree health and transpiration, and in turn affect the removal of gaseous pollutants by limiting gas exchange at the leaf surface were not considered. $PM_{2.5}$ could be removed from the atmosphere by the dry deposition process to bark of the deciduous trees during the leaf-

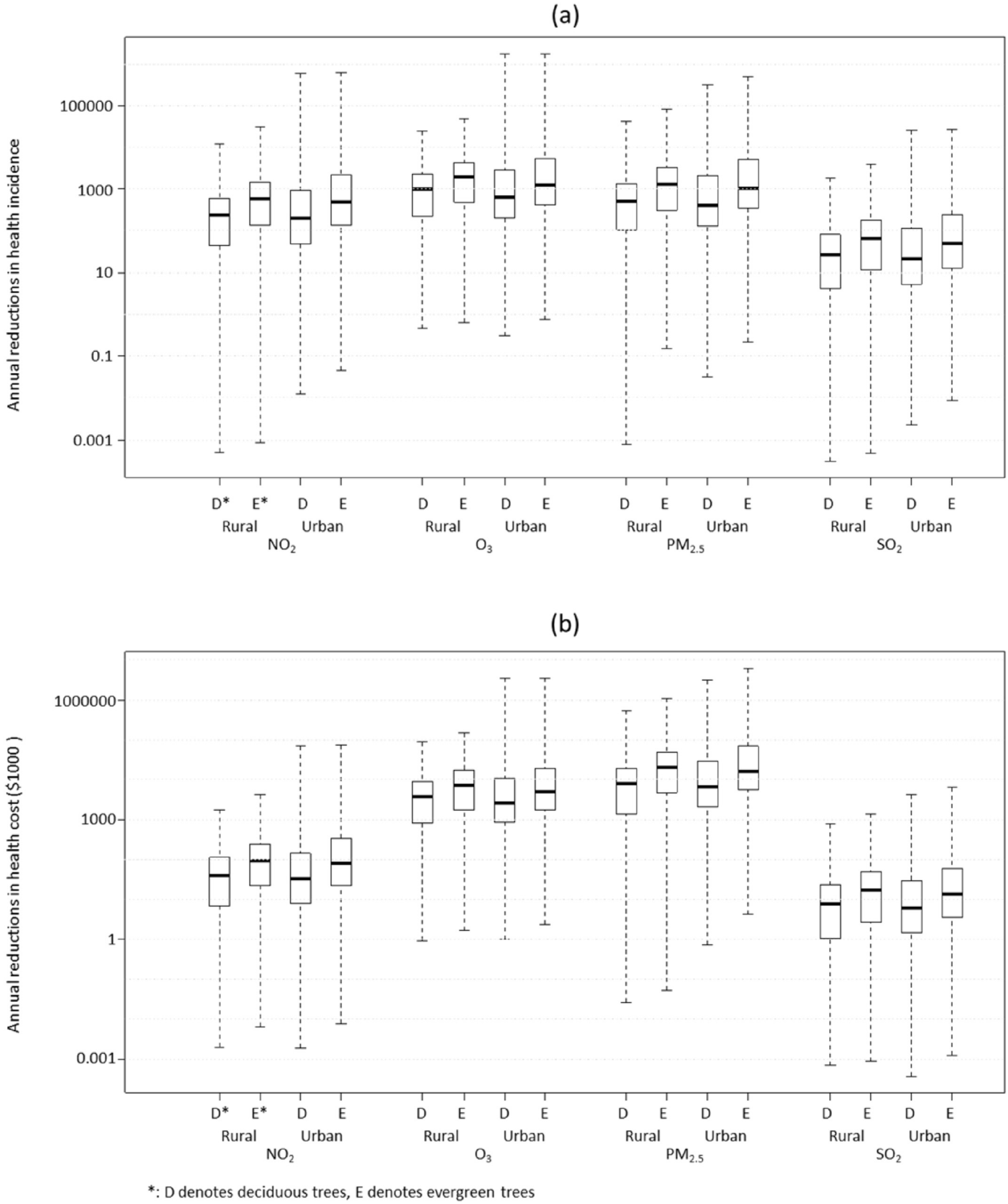

Fig. 3. Distribution of (a) annual reductions in health incidence and (b) annual reductions in health cost across the entire study area.

off season, though this process was not accounted for since bark area index (BAI) was not readily available across the conterminous United States. Of the six criteria air pollutants, only four air pollutants were analyzed due to the limitation of BenMAP.

Despite the limitations, there are various advantages to the developed database. The estimates were derived employing the

Table 2
Example of developed database entries for Onondaga County, NY.

County	Area	TC (%)	LAI	Leaf type	Air pollutant	Removal (t)	Conc. change[a] (ppb or μg m^{-3})		Health effect Category	Incidences	($)
Onondaga	Rural	54.2	5	D[b]	NO_2	14	1Max	0.005	ARS	0.12	4
					O_3	2802	1Max	0.33	ARS	80.10	6847
							3Mean	0.23	ERV	0.03	13
							4Mean	0.19	HA	0.08	2645
							8Max	0.24	M	0.05	363,993
							8Mean	0.21	SLD	32.34	3175
							24Mean	0.11			
							24MeanQ	0.11			
					$PM_{2.5}$	135	1Max	0.11	ARS	27.09	2655
					SO_2	107	1Max	0.016	ARS	0.25	8
				E[c]	NO_2	102	1Max	0.024	ARS	0.90	28
					O_3	4792	1Max	0.67	ARS	160.69	13,737
							3Mean	0.44	ERV	0.06	27
							4Mean	0.34	HA	0.17	5289
							8Max	0.48	M	0.09	728,667
							8Mean	0.44	SLD	65.44	6426
							24Mean	0.22			
							24MeanQ	0.22			
					$PM_{2.5}$	386	1Max	0.39	ARS	104.15	10,208
					SO_2	186	1Max	0.03	ARS	0.52	16
	Urban	39.6	5	D[b]	NO_2	3	1Max	0.003	ARS	0.52	16
					O_3	659	1Max	0.22	ARS	364.56	31,166
							3Mean	0.14	ERV	0.15	61
							4Mean	0.10	HA	0.39	12,280
							8Max	0.16	M	0.22	1,677,890
							8Mean	0.15	SLD	150.85	14,812
							24Mean	0.08			
							24MeanQ	0.08			
					$PM_{2.5}$	32	1Max	0.08	ARS	131.93	12,931
					SO_2	25	1Max	0.01	ARS	1.16	37
				E[c]	NO_2	24	1Max	0.015	ARS	4.50	142
					O_3	1123	1Max	0.43	ARS	735.50	62,876
							3Mean	0.27	ERV	0.30	124
							4Mean	0.20	HA	0.80	24,788
							8Max	0.32	M	0.44	3,382,768
							8Mean	0.30	SLD	306.94	30,139
							24Mean	0.15			
							24MeanQ	0.15			
					$PM_{2.5}$	91	1Max	0.28	ARS	527.44	51,699
					SO_2	44	1Max	0.02	ARS	2.47	78

[a] Unit for concentration change is ppb for NO_2, O_3 and SO_2, and μg m^{-3} for $PM_{2.5}$.
[b] Deciduous.
[c] Evergreen.

currently best available measurements of tree, meteorology, air pollutant and population nationwide. The models were performed on a fine temporal resolution (hourly) basis, assessing interactions among weather conditions, air pollutant concentration, and resuspension and wash-off of $PM_{2.5}$, and summarized for a year. The models linked tree effects on air quality to human health benefits through BenMAP. With more than 33 million values, the developed database comprehensively covers possible forest structures, and these values can be used to readily produce estimates of air pollutant removal and concentration change as well as health impacts and associated monetary values by any forest configurations anywhere in the conterminous United States.

4. Conclusions

A comprehensive database of tree effects was developed for deciduous and evergreen trees with varying LAI for urban and rural areas of counties in the conterminous United States. The database stores annual removal and concentration changes of the four criteria air pollutants, NO_2, O_3, $PM_{2.5}$ and SO_2, and reductions in adverse health incidences and monetary values. Downscaling the county results readily provide a first order approximation of the annual air pollutant and human health benefits by trees in multiple scales, from individual trees to city-based or larger scales over time in the conterminous United States. Air pollutant removal and concentration change can be downscaled based on tree cover area and tree cover percent, respectively.

The new database will allow for more detailed estimates of air quality and human health benefits due to changes in LAI through time as forest structure changes. However, to better estimate the future tree effects, future scenarios of local weather, air quality, population density and urban developments should be employed. Such data could include weather forecast data from North American Regional Climate Change Program (NARCCAP) (NARCCAP, 2015), air quality from EPA Office of Research and Development's Global Change Air Quality Assessment (Loughlin et al., 2007), land use forecast from Integrated Climate and Land Use Scenarios (ICLUS) (US EPA, 2015d).

Based on the analyses, the following conclusions can be drawn:

1. Rural-evergreen, rural-deciduous, urban-evergreen, and urban-deciduous trees in this order had greater effects on air quality.
2. Urban-evergreen, urban-deciduous, rural-evergreen, and rural-deciduous trees in this order had greater effects on human health.

Table 3
Annual results for Syracuse, NY estimated by downscaling county results.

Air pollutant	Removal (t)	Conc. change (ppb or µg m^{-3})[a]			Health effect		
			D[b]	E[c]	Category	Incidences	($)
NO_2	0.6	1Max	0.0018	0.010	ARS	0.26	8
		3Mean	0.0008	0.006	AE	4.26	358
		4Mean	0.0007	0.004	ERV	0.003	1
		8Max	0.0008	0.006	HAR	0.008	243
		8Mean	0.0005	0.005			
		24Mean	0.0004	0.003			
		24MeanQ	0.0004	0.003			
O_3	66.2	1Max	0.15	0.30	ARS	108.17	9247
		3Mean	0.09	0.19	ERV	0.04	17
		4Mean	0.07	0.13	HA	0.10	3002
		8Max	0.11	0.22	M	0.06	472,195
		8Mean	0.10	0.20	SLD	39.80	3908
		24Mean	0.05	0.10			
		24MeanQ	0.05	0.10			
$PM_{2.5}$	3.7	1Max	0.057	0.19	AB	0.08	7
		3Mean	0.011	0.03	AMI	0.03	2392
		4Mean	0.008	0.02	ARS	49.97	4898
		8Max	0.019	0.07	AE	38.01	3090
		8Mean	0.012	0.04	CB	0.03	9652
		24Mean	0.006	0.02	ERV	0.04	18
		24MeanQ	0.006	0.02	HAC	0.012	473
					HAR	0.011	345
					LRS	1.00	52
					M	0.14	1,094,134
					URS	0.81	36
					WLD	8.39	1403
SO_2	2.5	1Max	0.006	0.013	ARS	0.31	10
		3Mean	0.003	0.006	AE	2.90	229
		4Mean	0.003	0.005	ERV	0.010	4
		8Max	0.003	0.007	HAR	0.013	409
		8Mean	0.003	0.005			
		24Mean	0.001	0.003			
		24MeanQ	0.001	0.003			

[a] Unit for concentration change is ppb for NO_2, O_3 and SO_2, and µg m^{-3} for $PM_{2.5}$.
[b] Deciduous.
[c] Evergreen.

3. Air pollutant removal, concentration changes, health incidences and values increased as LAI increased for all combination of air pollutant, leaf and area types; however, the relationship for NO_2, O_3 and SO_2 was non-linear whereas for $PM_{2.5}$ was almost linear.
4. Due to the greatest concentration for O_3 nationwide, annual removal and concentration changes were greatest for O_3 for all combinations of the leaf and area types.
5. Adverse health effects with the highest reductions in incidences were Acute Respiratory Symptoms associated with O_3 and $PM_{2.5}$, Asthma Exacerbations associated with NO_2 and $PM_{2.5}$, and School Loss Days associated with O_3
6. Adverse health effects with the highest values were Mortality associated with O_3 and $PM_{2.5}$.
7. Annual flux of air pollutant, F_a was sensitive to annual air pollutant concentration, C_a for the four air pollutants.
8. Annual air pollutant removal, R_a was impacted by tree cover area (m^2) for the four air pollutants.
9. Annual concentration changes were affected by tree cover % for NO_2, O_3 and $PM_{2.5}$, while by annual flux and concentration for SO_2.

References

Baldocchi, D.D., Hicks, B.B., Camara, P., 1987. A canopy stomatal resistance model for gaseous deposition to vegetated surfaces. Atmos. Environ. 21 (1), 91–101.
Barbour, M.G., Burk, J.H., Pitts, W.D., 1980. Terrestrial Plant Ecology. The Benjamin/Cummings Publishing Company, Inc.
Beckett, K.P., Freer-Smith, P.H., Taylor, G., 1998. Urban woodlands: their role in reducing the effects of particulate pollution. Environ. Pollut. 99, 347–360.
Cardelino, C.A., Chameides, W.L., 1990. Natural hydrocarbons, urbanization, and urban ozone. J. Geophys. Res. 95 (D9), 13,971–13,979.
Chameides, W.L., Lindsay, R.W., Richardson, J., Kiang, C.S., 1988. The role of biogenic hydrocarbons in urban photochemical smog: Atlanta as a case study. Science 241, 1473–1475.
Fann, N., Lamson, A.D., Anenberg, S.C., Wesson, K., Risley, D., Hubbell, B., 2012. Estimating the national public health burden associated with exposure to ambient $PM_{2.5}$ and ozone. Risk Anal. 32, 81–95.
Fowler, D., 1980. Removal of sulphur and nitrogen compounds from the atmosphere in rain and by dry deposition. In: Drablos, D.T. (Ed.), Ecological Impact of Acid Precipitation. Proceedings of an International Conference, in Sandefjord, Norway. SNSF project, Oslo, Norway, pp. 22–32.
Gualtieri, G., Tartaglia, M., 1998. Predicting urban traffic air pollution: a GIS framework. Transp. Res. Part D Transp. Environ. 3 (5), 329–336.
Heisler, G.M., 1986. Energy savings with trees. J. Arboric. 12 (5), 113–125.
Hirabayashi, S., Kroll, C.N., Nowak, D.J., 2011. Component-based development and sensitivity analyses of an air pollutant dry deposition model. Environ. Model. Softw. 26, 804–816.
Hirabayashi, S., Kroll, C.N., Nowak, D.J., 2015. i–Tree Eco Dry Deposition Model Descriptions. http://www.itreetools.org/eco/resources/iTree_Eco_Dry_Deposition_Model_Descriptions.pdf (accessed October, 2015).
Hodan, W.B., Barnard, W.R., 2004. Evaluating the contribution of PM2.5 precursor gases and re-entrained road emissions to mobile source PM2.5 particulate matter emissions. MACTEC under contract Fed. Highw. Adm. 53. http://www3.epa.gov/ttnchie1/conference/ei13/mobile/hodan.pdf (accessed October, 2015).
i-Tree, 2015. i–Tree: Tools for Assessing and Managing Community Forests. http://www.itreetools.org/ (accessed April, 2015).
Ito, K., De Leon, S., Thurston, G.D., Nadas, A., Lippmann, M., 2005. Monitor-to-monitor temporal correlation of air pollution in the contiguous US. J. Expo. Anal. Environ. Epidemiol. 15, 172–184.
Jenson, S.S., 1998. Mapping human exposure to traffic air pollution using GIS. J. Hazard. Mater. 61, 385–392.
Judek, S., Stieb, D., Jovic, B., 2006. Air Quality Benefits Assessment Tool (AQBAT) Release 1.0. Health Canada, Ottawa.
Kane, J., 2012. Health Costs: How the U.S. Compares with Other Countries (accessed August, 2015). http://www.pbs.org/newshour/rundown/health-costs-how-the-us-compares-with-other-countries.
Koller, M., Upadhyay, S.K., 2005. Prediction of processing tomato yield using a crop

growth model and remotely sensed aerial image. Trans. Am. Soc. Agric. Eng. 48 (6), 2335–2341.
Loughlin, D., Johnson, T., Shay, C., Hemming, B., Bierwagen, B., Grambsch, A., Benjey, W.G., 2007. Projecting future-year pollutant emissions: emerging approaches from the EPA ORD global change air quality assessment. In: 16th Annual International Emissions Inventory Conference. Raleigh, NC, 14-17 May, 2007.
Multi-Resolution Land Characteristics Consortium (MRLC), 2015. National Land Cover Database 2001 (NLCD 2001). http://www.mrlc.gov/nlcd01_data.php (accessed July, 2015).
Murphy, C.E., Sigmon, J.T., 1990. Dry deposition of sulfur and nitrogen oxide gases to forest vegetation. In: Lindberg, S.E., Page, A.L., Norton, S.A. (Eds.), Acid Precipitation, Sources, Deposition, and Canopy Interactions, vol. 3. Springer-Verlag, New York, New York, pp. 217–240.
National Climatic Data Center (NCDC), 2015a. U.S. Climate Normals: Freeze/Frost Data. http://www.ncdc.noaa.gov/cgi-bin/climatenormals/climatenormals.pl?directive=prod_select2&prodtype=CLIM2001&subrnum= (accessed July, 2015).
National Climatic Data Center (NCDC), 2015b. Climate Data Online. http://www.ncdc.noaa.gov/cdo-web/ (accessed July, 2015).
National Oceanic and Atmospheric Administration (NOAA), 2015. NOAA/ESRL Radiosonde Database. http://www.esrl.noaa.gov/raobs/ (accessed July, 2015).
North American Regional Climate Change Assessment Program (NARCCAP), 2015. North American Regional Climate Change Assessment Program. http://www.narccap.ucar.edu/ (accessed October, 2015).
Nowak, D.J., 1994. Air pollution removal by Chicago's urban forest. In: McPherson, E.G., Nowak, D.J., Rowntree, R.A. (Eds.), Chicago's Urban Forest Ecosystems: Results of the Chicago Urban Forest Climate Project, United States Department of Agriculture, Forest Service General Technical Report NE-186, pp. 63–81. Radnor, PA.
Nowak, D.J., Greenfield, E.J., 2012. Tree and impervious cover in the United States. Landsc. Urban Plan. 107, 21–30.
Nowak, D.J.S., Hirabayashi, A., Bodine, R., Hoehn, 2013. Modeled $PM_{2.5}$ removal by trees in ten U.S. cities and associated health effects. Environ. Pollut. 178, 395–402.
Nowak, D.J.S., Hirabayashi, A., Bodine, E., Greenfield, 2014. Tree and forest effects on air quality and human health in the United States. Environ. Pollut. 193, 119–129.
Rasmussen, K.H., Taheri, M., Kabel, R.L., 1975. Global emissions and natural processes for removal of gaseous pollutants. Water, Air, Soil Pollut. 4, 33–64.
Saltelli, A., Chan, K., Scot, E.M., 2000. Sensitivity Analysis. John Wiley & Sons, West Sussex, UK.
Sarnat, S.E., Klein, M., Sarnat, J.A., Flanders, W.D., Waller, L.A., Mulholland, J.A., Russell, A.G., Tolbert, P.E., 2010. An examination of exposure measurement error from air pollutant spatial variability in time-series studies. J. Expo. Sci. Environ. Epidemiol. 20, 135–146.
Scurlock, J.M.O., Asner, G.P., Gower, S.T., 2001. Global Leaf Area Index from Field Measurements, 1932-2000. Data Set. Available on-line. http://www.daac.ornl.gov. from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/584.
Smith, W.H., 1990. Air Pollution and Forest. Springer-Verlag, New York.
United States Census Bureau (US Census Bureau), 2015. 2010 Census Urban and Rural Classification and Urban Area Criteria. http://www.census.gov/geo/reference/ua/urban-rural-2010.html (accessed July, 2015).
United States Environmental Protection Agency (US EPA), 1995. PCRAMMET User's Guide. Research Triangle Park, NC: United States Environmental Protection Agency.
Unite States Environmental Protection Agency (US EPA), 2015a. National Ambient Air Quality Standards (NAAQS). http://www.epa.gov/air/criteria.html (accessed July, 2015).
United States Environmental Protection Agency (US EPA), 2015b. Environmental Benefits Mapping and Analysis Program (BenMAP). http://www2.epa.gov/benmap (accessed July, 2015).
United States Environmental Protection Agency (US EPA), 2015c. Download Detailed AQS Data. http://www.epa.gov/ttn/airs/airsaqs/detaildata/download-aqsdata.htm (accessed July, 2015).
United States Environmental Protection Agency (US EPA), 2015d. Integrated Climate and Land Use Scenarios (ICLUS). http://www.epa.gov/ncea/global/iclus/ (accessed July, 2015).
Wang, J.T.A., Endreny, D.J., Nowak, 2008. Mechanistic simulation of tree effects in an urban water balance model. J. Am. water Resour. Assoc. 44, 75–85.
World Health Organization (WHO), 2002. The World Health Report 2002: Reducing Risks. Promoting Healthy Life. WHO, Geneva.