



Air pollution removal by trees in public green spaces in Strasbourg city, France[☆]



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ABSTRACT

This study integrates i-Tree Eco model in order to estimate air pollution removal by urban trees in Strasbourg city, France. Applied for the first time in a French city, the model shows that public trees, i.e., trees managed by the city, removed about 88 t of pollutants during one year period (from July 2012 to June 2013): about 1 ton for CO; 14 tons for NO₂; 56 tons for O₃; 12 tons for PM_{10coarse} (particles with diameter ranging from 2.5 to 10 µm); 5 tons for PM_{2.5} and 1 ton for SO₂. Air pollution removal varied mainly with the tree cover and the level of air pollutants concentrations. Comparison between simulated pollution removal rates and local emissions shows that public trees of Strasbourg reduce about 7% of the emitted PM_{10coarse} in the city's atmosphere; however, effect on other air pollutants is small. Thus, our study reveals that urban trees are a significant element to reduce air pollution but are not the only solution to this problem. It's then recommended to associate planting and managing urban forest resources to other strategies that take into account the urban environment characteristics: built structures, street design, location of local sources; etc.

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1. Introduction

Cities concentrate many problems that can affect human well-being (Bolund and Hunhammar, 1999). They hold the majority of human activities and the associated air pollution emissions

Abbreviations: ASPA, "Association pour la Surveillance et l'Etude de la Pollution Atmosphérique en Alsace" (Non-profit organization for monitoring and studying atmospheric pollution in Alsace); CIGAL, "Coopération pour l'information géographique en Alsace" (Cooperation for geographic information in Alsace); DBH, diameter at breast height; EEA, European Environment Agency; EMEP/EEA, European Monitoring and Evaluation Program/European Environment Agency; EMS, "Eurométropole de Strasbourg" (Eurometropolis of Strasbourg); LAI, Leaf Area Index; MEDDE, "Ministère de l'Écologie, du Développement Durable et de l'Énergie" (Ministry of ecology/sustainable development and energy); NOAA, National Oceanic and Atmospheric Administration; PADD, "Projet d'Aménagement et de Développement Durable" (Project of Planning and Sustainable Development); SERTIT, "Service régional de traitement d'image et de télédétection" (Regional Service of Image Treatment and Remote Sensing); UFORE, Urban Forest Effects Model; UNEP, "Union National des Entreprises du Paysage" (national union of landscape companies); VOC, volatile organic compounds; WHO, World Health Organization.

[☆] This study is a first-time estimate in France that assesses the role of urban trees to reduce air pollution. Comparison of removal rates with emissions rates in Strasbourg city shows that trees modestly remove air pollution.

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with consequent adverse health effects including pre-mature mortality and morbidity from cardiovascular and respiratory causes (Brunekreef and Holgate, 2002; Heinrich and Wichmann, 2004; WHO, 2006; Rückerl et al., 2011). Despite efforts conducted by European countries (EU) to reduce air pollutant emissions and improve air quality, urban population are still exposed to high levels of pollutant concentrations that exceed the EU standards to protect human health. For instance, the European Environment Agency (EEA) shows that during 2010 and 2012 respectively 21–30% and 64–83% of the European urban citizens were exposed to particulate matter concentrations above the EU daily limit values (50 µg/m³) and the World Health Organization (WHO) annual reference level (20 µg/m³) (EEA, 2014a). In 2011, fine particulate matter (PM_{2.5}) concentrations caused about 458 000 premature deaths in Europe (EEA, 2014a). France is no exception to air pollution issues; in 2012 about 5.4% of urban population in France is exposed to PM₁₀ concentrations above the EU daily limit value (50 µg/m³) (EEA, 2014b). In addition, a recent study conducted in Paris between 2007 and 2011 analyzed the link between the increased air pollution and hospital admission. An increase of NO₂, PM_{2.5} and PM_{10coarse} caused a 1.8%, 2.1% and 3.2% increase, respectively, in hospital consultations associated to asthma attacks among children between 2 and 14 years of age (Chatignoux and Host, 2013).

In April 2015, the European commission warned the French government because European limits for particle matter were not being met in some cities (Sénat, 2015). Hence, several policy instruments have to be implemented to meet European air quality directives. For example, the French Ministry of Ecology, Sustainable Development and Energy (MEDDE) has launched a program called “respirable cities” where 20 local authorities, including the Strasbourg metropolis will implement actions regarding transportation, energy use, and city planning. This initiative is designed to improve air quality in the medium term. Additionally an “air quality certificate” will promote use of low emission vehicles in city centers (MEDDE, 2015). These actions will complement other local measures such as the current development of public transportation and renewable energy production and use. Policies to reduce air pollution focus on the reduction of the emissions that are the main driver of the air pollution.

Some studies have suggested that new materials for buildings could contribute to air pollution reduction (Boonen et al., 2015; Angelo et al., 2013; Boonen and Beeldens, 2013; Chen and Poon, 2009; etc.), others show that planting vegetation has a substantial effect on air pollution (Escobedo et al., 2011; Currie and Bass, 2008; Nowak et al., 2006; etc.). The advantage of planting trees in the city is not only to reduce air pollution but also to answers to other social needs (e.g., recreation, cultural, aesthetic, etc.) without additional cost. However, while urban trees are considered as one key element to improve urban environment, its potential is often not considered in urban policies documents.

A growing number of studies have identified and quantified various ecosystem services provided in urban context like reduction of air pollution due to dry deposition function (Nowak, 2000; Nowak et al., 2006); regulation of temperature (e.g., shading and evapotranspiration) with the consequent reduction of the urban heat island (Yang et al., 2005) and carbon sequestration with its consequence on Climate Change mitigation. Nevertheless few disservices are noted in specific cases: emissions of volatile organic compounds (VOC) by trees (Owen et al., 2003) and local increase of air pollution in case of densely trees plantation (Tiway and Kumar, 2014). A simulation of trees and shrubs effects on particle dispersion at the street scale in Strasbourg city showed an increase of particle concentration in street canyon planted with densely trees foliation (Wania et al., 2012). Despite the recognition of these services and disservices, the lack of information about the potential of trees to alleviate urban environment problem and the underlying trees-atmosphere interactions is still important. This knowledge gap is due to the complexity of the physical and chemical processes involved in the trees-atmosphere interactions within urban areas and the lack of numerical models that quantify these processes (Cherlin et al., 2015). Hence, models like Citygreen, UFORE (Urban Forest Effects Model now known as i-Tree) and STRATUM (now known as i-Tree streets) were developed to assess these interactions, to quantify ecological services and disservices provided by urban trees and to provide more comprehensive analysis.

In France, the assessment of ecosystem services provided by urban green spaces has been lacking. This dearth of information is associated with an absence of a conceptual framework and the reluctance of some French researchers to use the “ecosystem service” concept as it is always considered as an exclusively economic concept (Froger et al., 2012). Therefore, as shown by Selmi (2014), the economic evaluation is emphasized at the expense of understanding the potential of vegetation to provide ecosystem services. To better understand this issue, this study is a first order estimation of one ecosystem service (air pollution removal) provided by trees in a French city. We present the underlying ecological assessment, showing that it could provide relevant information to guide urban planning and management. The main objective of this study is to

quantify the amount of air pollution removed by urban trees using i-Tree model (Nowak et al., 2008) in Strasbourg city, France.

Designed and developed by U.S. Department of Agriculture, Forest Service and several partner organizations (www.itreetools.org), the i-Tree Eco assesses urban forest structure and consequent ecosystem services and value. It has been used in several European cities including Barcelona, Spain (Chapparo and Terradas, 2009; Baro et al., 2014); Torbay, United Kingdom (Rogers et al., 2011) and Florence, Italy (Paoletti et al., 2010) to demonstrate the potential of urban trees to improve environmental quality at the city scale. This paper presents an application of i-Tree Eco model in Strasbourg City and evaluates the removal rates in comparison with local emissions rates. It also discusses and offers in-depth perspectives to develop integrated green spaces management and sustainable urban policies to alleviate air pollution.

2. Methods

2.1. Study area

This study was conducted in Strasbourg, France (7830 ha; 48°35'N and 7°45'W) in North East France (Fig. 1). The city's population reached about 275 000 inhabitants in 2011 (INSEE, 2011). The climate of Strasbourg is continental with an average monthly temperature of 2 °C in January and 19 °C in June. The mean annual precipitation is 665 mm (Meteo France website: <http://www.meteofrance.com/accueil>). The Strasbourg Eurometropolis website (EMS) mentioned that the city has 400 ha of parks and is the only European city with protected alluvial forests around its outskirts, with three great forests: Neuhof (757 ha); Robertsau (493 ha) and Rohrschollen (309 ha) (EMS, 2013).

Though all trees in Strasbourg have an impact on air quality, this study focuses on urban trees located in public green spaces and street tree resources as this is the urban forest resource that could be managed via public funding. We assessed public urban green spaces as defined by Young (2010): “publicly managed natural resources assets in a city including street trees, parks, and natural areas”. Privately managed spaces were then excluded.

2.2. Air pollution removal: i-Tree eco model application

Modeling air pollution removal by trees in Strasbourg city was performed using the i-Tree Eco model. It combines trees data (number of trees; species; tree height; diameter at breast height (DBH); height to crown; tree cover; etc.) with local environmental data (hourly meteorological data; air pollution concentration data; etc.) to estimate hourly pollution removal by trees and shrub (Nowak and Crane, 2000; Nowak et al., 2006, 2014).

Since the main objective of this paper is to quantify air pollution removal by trees in public green spaces in Strasbourg, we focus only on the i-Tree Eco dry deposition (air pollution removal) module. The following paragraphs describe: (i) data collection and (ii) the calculation processes of air pollution removal.

2.2.1. Data collection

To perform air pollution removal quantification, the i-Tree model requires several types of data. Tree structure information (tree cover, leaf area index, percent evergreen) was input to the model along with local weather and pollution data. Boundary layer height data were also used to estimate percent air quality improvement due to the pollution removal by trees.

2.2.1.1. Sampling scheme and tree cover data. Tree structure information was collected following i-Tree Eco guidelines (i-Tree Eco User's Manual, 2013). The sampling design and data collection were carried out in four steps: (i) delimiting the public green spaces

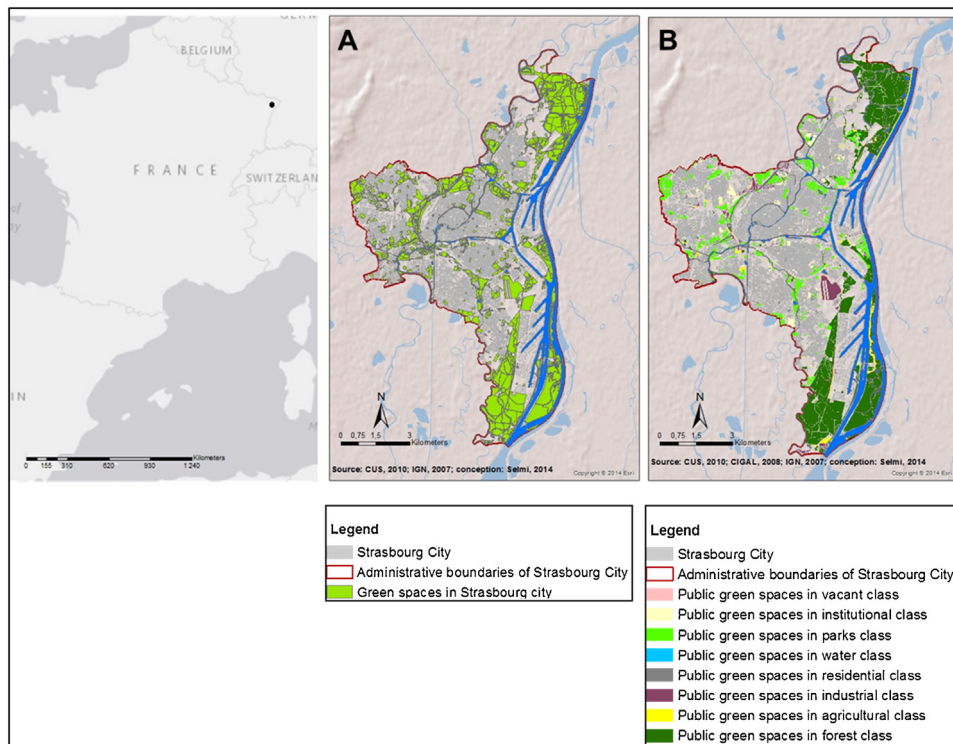


Fig. 1. Location of Strasbourg city, spatial distribution of green spaces within the city (A) and within the land use classes (Source: Selmi, 2014 after ESRI, Here, DeLorme, MapmyIndia, 2015; IGN, 2007; CIGAL, 2008; EMS, 2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

managed by municipal services in Strasbourg city; (ii) stratifying public green spaces within land use classes, (iii) assessing tree cover within public green spaces and (iv) generating field sample and collecting field data.

Field data were obtained from 228 plots randomly distributed within municipal green spaces of Strasbourg (Fig. 2) and stratified into land use classes based on 1:10000 land-cover database of the Alsace region provided by the Cooperation for Geographic Information in Alsace (CIGAL, 2008). The localization of plots was based on public green spaces map (EMS, 2010) and the percent of tree cover within public green spaces for each land use class was derived from 1:2000 tree cover map provided by the Regional Service of Image Treatment and Remote Sensing (SERTIT, 2012) (Table 1). The location of plots was defined using random plot generation functionality of ArcGIS (by generating x and y coordinates).

The field survey was conducted from April to July 2013. At each 0.04 ha circular plot, located using a GPS device and aerial orthophotographs, general information (date, plot address, GPS coordinates, land use, tree and shrub cover, ground cover and plantable space) were recorded as well as individual tree data on species, diameter at breast height (DBH), total tree height, crown width, height to base of live crown, crown light exposure, crown dieback percent, percent crown missing.

2.2.1.2. Hourly weather data and pollution data. Hourly meteorological data (e.g., wind speed, sky cover, temperature, liquid precipitation, etc.) were collected from the “Meteo France” (2 stations) and the National Oceanic and Atmospheric Administration (NOAA, 2016) (1 station) located also at Strasbourg city. Boundary layer data were obtained from the nearest monitoring station. The hourly pollution concentration data for ozone (O_3); sulfur dioxide (SO_2); nitrogen dioxide (NO_2); carbon monoxide (CO); particulate matter with diameters between 2.5 and $10\ \mu m$ ($PM_{10coarse}$) and less than $2.5\ \mu m$ ($PM_{2.5}$) were obtained from the regional Air Qual-

ity Agency (ASPA) in charge of the air pollution monitoring in the Alsace Region. These data were measured in six monitoring stations located within the study area over a one year period (from July 2012 to June 2013).

The dry deposition model of i-Tree Eco uses tree data, hourly weather and pollution concentration to quantify the hourly amount of pollution removal and the corresponding percent of improvement in air quality (Nowak et al., 2006, 2013, 2014).

2.2.2. Calculation of the air pollution removal by trees

2.2.2.1. Dry deposition. Dry deposition is considered as the mechanism by which vegetation removes air pollutant from the troposphere in non-precipitation period (Cavanagh, 2006; Schlesinger, 1979). It depends on nature and property of pollutant (e.g., gaseous/particles; density; diameter; form; etc.), nature and property of surfaces (e.g., size; roughness; chemical nature, etc.) and weather variables (wind speed and direction; temperature; solar radiation; air turbulence, etc.) (Roupsard, 2013). Once pollutants are accumulated on leaf tree surfaces, they are removed primarily in two ways: through leaf stomata uptake of gaseous pollutants and leaf interception of particulate matter (Nowak et al., 2006). The first process leads to the diffusion of pollutant into the inner part of leaves. Gases may also be absorbed or react with plant surfaces; while removal through the second process may be reduced by the re-suspension of intercepted particles from the leaf surfaces through wind action.

The i-Tree Eco dry deposition module is used to estimate pollution removal during non-precipitation periods throughout the year (Hirabayashi et al., 2011; Nowak, 1994; Nowak et al., 2006, 2013, 2014). The pollutant flux (F ; in $gm^{-2}s^{-1}$) is calculated as the product of the deposition velocity (V_d ; in ms^{-1}) and pollutant concentration (C ; in gm^{-3}):

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

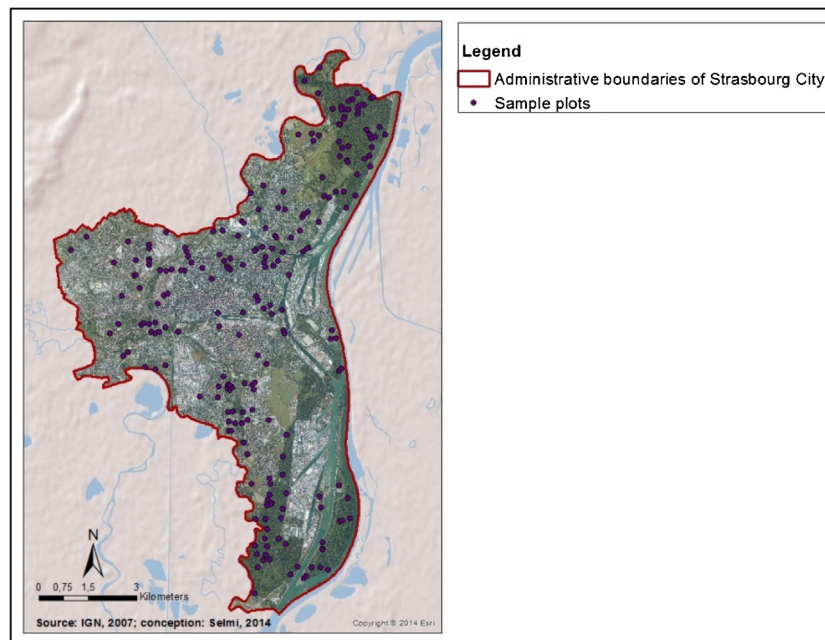


Fig. 2. Location of plots across Strasbourg city (Source: Selmi, 2014 after IGN, 2007).

Table 1
Strasbourg City data and sample data.

Land use class	Description	Total area(ha)	Municipal green spaces area (ha)	Number of plots	Sampled trees
Residential	Family and mixed residence	1902	54	40	134
Institutional	Hospital, universities, education and cultural centers, cemeteries	612	197	16	70
Industrial	Industry, commercial centers, port area	1615	136	8	25
Park	Parks, squares, open spaces	745	490	40	211
Vacant	Open spaces available for future urbanization project.	71	10	14	54
Agricultural	Agricultural fields	668	89	16	44
Forest	Forest, woodland	1456	1175	91	1417
Water	Riverbank vegetation	747	20	3	16
Total		7815	2171	228	1971

Deposition velocities are set to zero in the precipitation period (Nowak et al., 2006). For CO, NO₂, SO₂ and O₃ deposition velocities were calculated as the inverse of the sum of aerodynamic resistance (R_a), quasi-laminar boundary layer resistance (R_b), and canopy resistance (R_c):

$$V_d = (R_a + R_b + R_c)^{-1} \quad (2)$$

The aerodynamic resistance is independent of the air pollutant type. It is calculated using meteorological data while the quasi-laminar resistance and canopy resistance is calculated for each air pollutant (Hirabayashi et al., 2015). Hourly canopy resistance was calculated using the following equation:

$$1/R_c = 1/(r_s + r_m) + 1/r_{soil} + 1/r_t \quad (3)$$

where r_s is the stomatal resistance; r_m is the mesophyll resistance; r_{soil} is the soil resistance and r_t is the cuticular resistance.

The soil resistance was set to 2941 s m⁻¹ in growing season and 2000 s m⁻¹ otherwise (Hirabayashi et al., 2015). Stomatal resistance and cuticular resistance values were set from literature: for NO₂, $r_m = 100$ s m⁻¹ (Hosker and Lindberg, 1982) and $r_t = 20,000$ s m⁻¹ (Wesely, 1989); for O₃, $r_m = 10$ s m⁻¹ (Hosker and Lindberg, 1982) and $r_t = 10,000$ s m⁻¹ (Taylor et al., 1988; Lovett, 1994); for SO₂, $r_m = 0$ (Wesely, 1989) and $r_t = 8000$ s m⁻¹. The canopy resistance value for CO was set to 50,000 s m⁻¹ in the in-leaf season and 1,000,000 s m⁻¹ in the out-leaf season (Bidwell and Fraser, 1972).

The removal of CO by trees is not related to photosynthesis and transpiration. For PM_{10coarse}, the deposition velocity was set to 0.0064 m s⁻¹ based on data from Lovett (1994) assuming a 50% resuspension rate. For PM_{2.5} hourly deposition and resuspension rates are determined based on wind speed and leaf area as detailed in Nowak et al. (2013).

The base deposition velocity (V_d) is then adjusted according to local Leaf Area Index (LAI) based on local field data and local season variation (i.e., local leaf-on and leaf-off dates). For deciduous trees, the calculation of pollution deposition is limited to the in-leaf period. The leaf area index is the total leaf area (m²) divided by total canopy cover in city (m²).

Seasonal leaf area variation was estimated using a two-week period around leaf-on and leaf-off dates where the deciduous trees change from no leaves to full leaf and vice versa. Averages of these two dates were set based on French Phenological Collaborative Database (<http://www.gdr2968.cnrs.fr/>). In this study, mean leaf-on date was 28/04 and mean leaf-off date was 16/10.

The i-Tree model is a big-leaf multi-layer hybrid model (Baldocchi et al., 1987; Baldocchi, 1988); it does not differentiate effects among species but rather models the canopy as a whole to get its overall effect. That is, all canopies with the same leaf area index is treated equally and there is no differentiation of species in deposition velocities, though species will have differing effects based on the amount of leaf area within the study area.

2.2.2.2. Removal/emission ratio. Annual removal rates obtained from i-Tree Eco model were compared to 2012 emission estimates in Strasbourg city provided by the ASPA agency. Emission estimates (E) are considered as the pollutant flux emitted into the atmosphere by different sources and activities over a one year period (Jagielski and O'Brien, 1994). In Strasbourg city, assessed emissions are calculated for seven main sectors based on the European Monitoring and Evaluation Program and the European Environment Agency (EMEP/EEA) air pollutant emission inventory guidebook (EMEP/EEA, 2009): transformation of energy; residential; industrial; agricultural; services and commercial; road transportation and other mode of transportation. Emission estimates are based on coupling “bottom up” and “top-down” approach. The first approach, which is relevant at the local scale, is based on emission factors and local data provided by local sources (e.g., local factories, road traffic, number of housing) (Citeair, 2011; ASPA, 2014b). The second approach adjusts results from the bottom-up approach by applying statistical indicators (e.g., land use; population; etc.) to disaggregate regional, national or continental emissions assessments at local scale. In Strasbourg city, the ASPA agency combines both “bottom-up” and “top-down” approach to produce an emission inventory and monitor energy consumption of several sectors (ASPA, 2014b).

2.2.2.3. Air quality improvement. The boundary layer is defined as the region of the atmosphere that is directly influenced by the Earth's surface. It could reach few kilometers during daytime (1–3 km). The quantity of pollution within this boundary layer over the whole city (g) is calculated as the product of measured concentration (g m^{-3}), boundary layer height (m) and city area (m^2). This extrapolation from ground-layer concentration to total pollution within the boundary layer assumes a well-mixed boundary layer, which is common in the daytime (unstable conditions) (Colbeck and Harrison, 1985). Hourly percent air quality improvement is estimated as the removed pollution (g) divided by the sum of removed pollution (g) and the quantity of pollution within the boundary layer (g) (Nowak et al., 2006).

3. Results

3.1. Structure of strasbourg's public trees

Overall public green spaces occupy about 2171 ha (about 27.80% of the city area). Public green spaces are dominated in forest land uses (54.11%) followed by park (22.59%) and institutional (9.08%). The urban forest within public green spaces has an estimated 588,000 trees and the total amount of tree cover within Strasbourg city is about 2750 ha with about 1487 ha in public green spaces (about 54.07% of total tree cover in the city). Municipal trees cover about 19.02% of the city area and about 68.49% of public green spaces area. The highest percent of public tree cover occurs in forests (74.97%) followed by parks (15.25%) and institutional (3.27%). The low amount of public tree cover is on institutional land due to the domination of grass management. About 338.15 ha of municipal green spaces can support tree planting; approximately 37.90% and 33.90% of vacant land use class and parks in the city are considered as a plantable area. Urban forest manager could exploit these areas to plant trees (or other plants) to enhance air pollution removal and other ecosystem services. Trees with diameters less than 15.2 cm constitute 44 percent of the population and about 15 percent of Strasbourg trees population has diameters greater than 70 cm. The majority of large trees (with diameter greater than 54 cm) are located in agricultural and vacant class (30.0% and 22.0% respectively), while 49.0% of tree population in forest area has diameter less than 15.2 cm.

The three most common species are European beech (*Fagus sylvatica*) (12.0%), European filbert (*Corylus avellana*) (11.90%), and European ash (*Fraxinus excelsior*) (10.0%). Other species considered as top rated species for improving air quality were: Crimean linden (*Tilia Euchlora*) (11.0% of common species in institutional class), silver linden (*Tilia tomentosa*) (9.0% of common species in residential class), London plane (*Platanus x acerifolia*) (12.0% of common species in residential class) and Ginkgo (*Ginkgo biloba*) (3.0% of common species in institutional class).

The results of i-Tree Eco model show that municipal green space's leaf area is 90.76 km^2 with 51.56 km^2 in forest area, 25.87 km^2 in parks area, 5.22 km^2 in institutional class, 3.29 km^2 in industrial class, 1.0 km^2 in residential class, 0.33 km^2 in vacant places. The species with the greatest leaf area were European beech (*Fagus sylvatica*) (14.70%) followed by European ash (*Fraxinus excelsior*) (10.10%) and sycamore maple (*Acer pseudoplatanus*) (10.0%).

3.2. Assessment of trees impact

Trees in public green spaces in Strasbourg removed about 88.23 t per year (t year^{-1}) of pollutants from July 2012 to June 2013: 1.20 t year^{-1} for CO; 13.84 t year^{-1} for NO₂; 55.88 t year^{-1} for O₃; 11.77 t year^{-1} for PM_{10coarse}; 4.51 t year^{-1} for PM_{2.5} and 1.04 t year^{-1} for SO₂ (Table 3). Pollutant removal varies depending on seasons. During the in-leaf season, total estimated pollutant removal was 71.82 t year^{-1} : 1.07 t year^{-1} for CO; 8.83 t year^{-1} for NO₂; 48.68 t year^{-1} for O₃; 8.46 t year^{-1} for PM_{10coarse}; 4.08 t year^{-1} for PM_{2.5} and 0.70 t year^{-1} for SO₂ (Table 2). Therefore, 81% of yearly estimated air pollution removal was recorded in the leaf-on season due to the greater leaf area and often higher pollutant concentrations (e.g., ozone).

The annual pollution removal is calculated by multiplying the total tree cover (m^2) by the annual pollutant flux (g m^{-2}). Minimum and maximum estimates of removal of NO₂, O₃, PM_{10coarse}, PM_{2.5} and SO₂ are computed with varying the in-leaf dry deposition velocities depending on typical range of published values (Lovett, 1994).

The amount of pollutant removal varies monthly with peak removal in September 2012 for CO (0.26 t) and NO₂ (1.69 t), in June 2013 for O₃ (10.66 t), SO₂ (0.17 t) and PM_{10coarse} (2.40 t) and in July 2013 for PM_{2.5} (1.02 t) (Fig. 3). This variation is influenced by the in-leaf season, which extends in Strasbourg over six months from April to October. Other factors like warmer air temperature and reduced wind speed in the summer season contribute to increase of air pollutant concentrations and therefore increase deposition velocities for many pollutants.

In term of annual pollutant removal per square meter of tree cover, total pollutant removal was 5.89 g m^{-2} of tree cover year⁻¹; it was 0.08 g m^{-2} of tree cover year⁻¹ for CO; 0.92 g m^{-2} of tree cover year⁻¹ for NO₂; 3.73 g m^{-2} of tree cover year⁻¹ for O₃; 0.79 g m^{-2} of tree cover year⁻¹ for PM_{10coarse}; 0.30 g m^{-2} of tree cover year⁻¹ for PM_{2.5} and 0.07 g m^{-2} of tree cover year⁻¹ for SO₂.

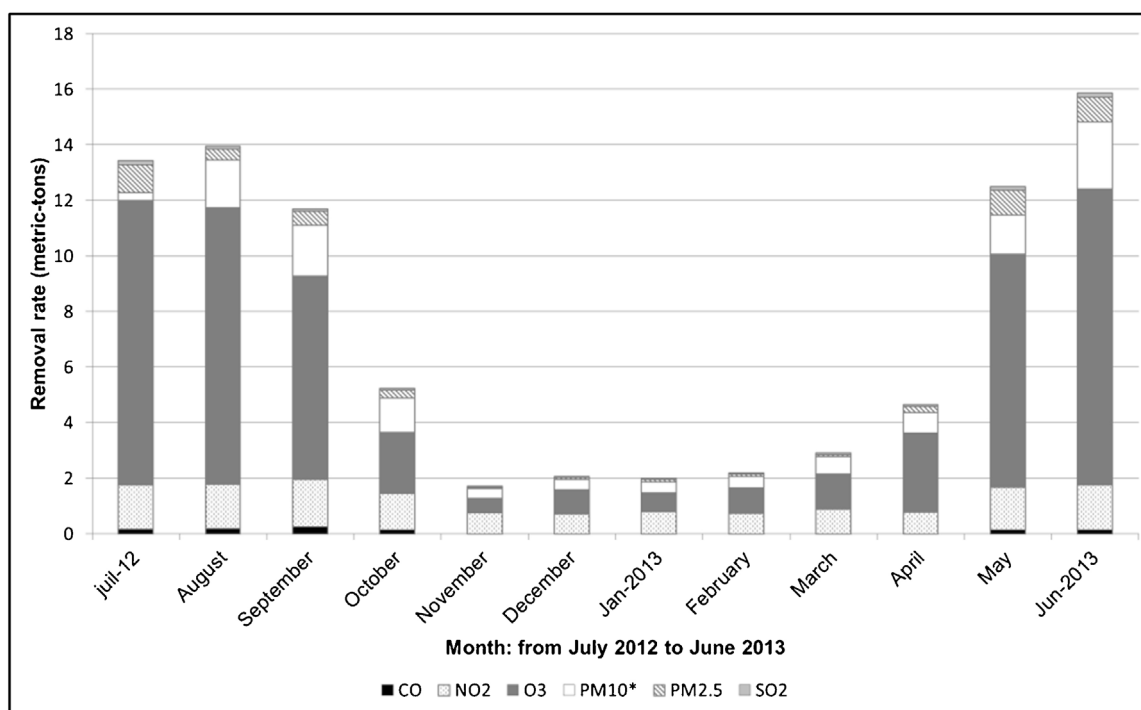
Total pollution removal varies among land use classes. The forest land use removed the most pollution (50.13 t year^{-1}); followed by parks (25.15 t year^{-1}); institutional lands (5.08 t year^{-1}); industrial lands (3.20 t year^{-1}) and agricultural areas (2.62 t year^{-1}). Residential area; water areas and vacant class had the lowest removal at 0.98 t year^{-1} ; 0.76 t year^{-1} ; 0.32 t year^{-1} respectively. This pattern of removal is related to the amount of tree cover in each land use class (Table 3).

A comparison between the amount of pollution removal and the amount of pollution emission in Strasbourg shows that trees within municipal green spaces removed about 0.03% of the emitted CO; 6.60% of the emitted PM_{10coarse}; 1.50% for the emitted PM_{2.5} and 0.50% for the emitted SO₂ (Table 4). It is important to note that not all pollution in Strasbourg is derived from local emissions and some pollutants, such as PM_{2.5}, can be formed from chemical reactions.

Table 2

Annual pollution removal (July 2012 to June 2013) and in-leaf season pollution removal by trees in Strasbourg.

Pollutants	Annual air pollution removal rate			Air pollution removal in the in-leaf season		
	Min	t year ⁻¹	Max	Min	t year ⁻¹	Max
CO	1.20	1.20	1.20	1.07	1.07	1.07
NO ₂	8.22	13.84	17.14	3.21	8.83	12.13
O ₃	18.14	55.88	73.84	10.94	48.68	66.64
PM _{10coarse}	4.60	11.77	18.39	3.30	8.46	13.22
PM _{2.5}	0.61	4.51	9.11	0.55	4.08	8.25
SO ₂	0.64	1.04	1.62	0.30	0.70	1.29

**Fig. 3.** Monthly pollution removal (July 2012–June 2013) by trees in Strasbourg city.**Table 3**

Air removal pollution rate over the different land use classes.

Land use	Tree cover (ha)	Pollution Removal (t year ⁻¹)						
		CO	NO ₂	O ₃	PM _{10coarse}	PM _{2.5}	SO ₂	Total
Agriculture	30.57	0.04	0.41	1.66	0.35	0.13	0.03	2.62
Forest	1114.80	0.68	7.86	31.74	6.68	2.56	0.59	50.13
Industrial	28.50	0.04	0.50	2.03	0.43	0.16	0.04	3.20
Institutional	48.65	0.07	0.80	3.22	0.68	0.26	0.06	5.08
Park	226.87	0.34	3.95	15.93	3.35	1.29	0.30	25.15
Residential	28.46	0.01	0.15	0.62	0.13	0.05	0.01	0.98
Vacant	2.54	0.004	0.05	0.20	0.04	0.02	0.003	0.32
Water	6.59	0.01	0.12	0.48	0.10	0.04	0.01	0.76
Total		1.20	13.84	55.88	11.77	4.51	1.04	88.23

Table 4

Comparison between pollution removal and pollution emission across Strasbourg city and percent of air quality improvement in Strasbourg city.

Pollutants	Pollution removal (R) (t year ⁻¹)	Pollution Emission(E) (t year ⁻¹) (ASPA, 2014b)	Pollution removal ratio (R/E × 100) (%)	Percent of air quality improvement (%)
CO	1.20	3910	0.03	0.002
NO ₂	13.84	NO ₂ emissions are not calculated. NO _x emissions are about: 2633	0.50	0.4
PM _{10coarse}	11.76	177	6.60	1
PM _{2.5}	4.50	308	1.50	0.2
SO ₂	1.03	209	0.50	0.4
O ₃	56	–	–	0.6

Additionally, the efficiency of public trees can be assessed in comparison with the air pollution content within the boundary layer. These concentrations are the result of the transport and the transformation of emissions through meteorological and local factors. The percent of air quality improvement by public trees throughout Strasbourg city is lower than 0.5%. It varies among pollutant with greatest percent removal occurring for PM_{10coarse}, ozone and nitrogen dioxide (Table 4).

The removal rate in Strasbourg city (5.89 g m^{-2} of tree cover year⁻¹) is comparable to removal rates in urban areas of the United States (6.7 g m^{-2} of tree cover year⁻¹). However, the removal rate in Strasbourg was lower than several U.S. cities: Los Angeles (23.1 g m^{-2} of tree cover year⁻¹); Washington (11.3 g m^{-2} of tree cover year⁻¹), New York (13.5 g m^{-2} of tree cover year⁻¹) and Minneapolis (6.2 g m^{-2} of tree cover year⁻¹) (Nowak et al., 2006). Removal rates vary among areas due to several factors such as pollution concentrations, local weather conditions, leaf area index, percent evergreen tree cover and length of growing season (Nowak et al., 2006, 2013, 2014).

Since the model does not differentiate pollution removal by species, we distributed the species effect proportional to species leaf area. Based on pollution removal proportional to leaf area, the European beech (*Fagus sylvatica*) which dominates the forest sector, removed about 21% of air pollution in this class followed by European Ash (*Fraxinus excelsior*) (17%), English Oak (*Quercus robur*) (12%) and sycamore maple (*Acer pseudoplatanus*) (10%). In the residential sector silver linden (*Tilia tomentosa*), London plane (*Platanus x acerifolia*) and horsechestnut (*Aesculus hippocastanum*) respectively removed 12%, 11% and 11% of the pollution removal (Table 5).

4. Discussion

This paper explores the ability of public trees to improve air quality in Strasbourg city through dry deposition of pollutants. Results indicate that from July 2012 to June 2013, public trees removed about 88 t of air pollution, which varies depending on pollutant, amount of tree cover and seasons. Through a high level of public trees and urban green spaces in Strasbourg, which is one of the top Ten French Cities in green space surfaces according to the national union of landscape companies (UNEP, 2014); public trees remove a small part of air pollution, but are estimated to remove about 7% of PM_{10coarse} emissions in the city. As this study only investigated trees in public green spaces, trees in private green spaces would increase total air pollution removal in the city, but these trees are not easily controlled by urban managers. Future research focusing air pollution removal by the overall tree cover is recommended to quantify ecosystem services provided by the whole urban forest across the city of Strasbourg.

Urban trees help to mitigate air pollution, but they are one of many potential solutions to this problem. Reducing emissions from the source prevents pollutant emissions and trees should not be used as alternate solution to emission reduction, but rather as complementary one. Through not investigated in this study, trees can reduce pollutant emissions by lower air temperatures and/or reducing building energy use. However, tree can also produce particles (e.g., pollen), limit pollutant dispersion and thus increase local pollutant concentrations (e.g., near roadways) (e.g., Gromke and Ruck, 2009; Wania et al., 2012; Salmond et al., 2013). Hence, Planting and managing trees should be associated with other integrative planning strategies usually based on either technological (e.g., more energy efficient technology) or non-technological measures (e.g., built and organize cities to reduce energy consumption and associated emissions). A recent study conducted in Alsatian region (France) show that the replacement of 20% of individual boiler

by collective ones and the improvement of boiler efficiency can decrease to 15% of PM₁₀ emission from residential sector (Selmi et al., unpublished data).

While climate considerations and air quality information continue to be incorporated into urban planning process, ecosystem services provided by urban vegetation remain largely unaccounted despite scientific evidence. In the Strasbourg metropolitan, a recent investigation, based on participatory decision-making, shows that developing a tramway network, creating car-free spaces and reducing air pollution are the principal environmental issues for inhabitants (ASPA, 2014a). Nevertheless, the influence of urban vegetation on human well-being was not mentioned. In another recent project of planning and sustainable development (PADD), there is focus on the development of urban greenway (green spaces network), but unfortunately, only its social and aesthetic considerations are taking into account (ADEUS, 2015). These projects reveal that planners and residents need more information/education about the services and values provided by urban vegetation. In addition, all ecosystem services (e.g., social, ecological and environmental) provided by urban green spaces and urban trees need to be considered in the planning process. Awareness of multipurpose aspect of green spaces and ecosystem services should also identify and resolve conflicts of interest between them.

In Strasbourg city, a wide range of street trees are regularly pruned to give them a geometric design and for safety reasons. As this pruning is done, managers should consider local traffic emissions to design canopy structure that is healthy with maximum leaf area, it allow for dispersion of local pollutants or limit dispersion toward sidewalks where people are often exposed to pollutant emissions. In addition, limited use of fossil fuels to maintain the trees (e.g., emissions from vehicles and equipment used to prune trees) could reduce local pollutant emissions (e.g., Nowak et al., 2002a,b). Pollution removal rates are influenced by tree condition and size. Healthy large trees remove about 60 times more pollution annually than healthy small trees (Nowak, 1994). Hence, sustaining large healthy trees could improve air quality in cities by enhancing leaf surface area to remove pollutants.

Quantifying pollution removal among the land use classes revealed a disparity in trees distribution across the city and pollution removal levels. Mapping this unequal distribution of trees along human population data could be used to ensure more equitable distribution of trees and ecosystem services as well as enhance urban sustainable planning within the city. More research is needed on the spatial distribution of ecosystem services provided by urban trees.

Information given by the i-Tree Eco model like “plantable area” can be used by urban forest managers to plant trees (or other plants) and enhance air pollution removal and other associated ecosystem services. The plantable area in the vacant land use class, which often support of new urbanization projects, could also be used to create new green spaces to help improve air quality and as test sites to examine interactions among management practices, vegetation structure and its effects on local air pollution. Such test sites could be used to assess and improve the efficiency of vegetation in improving air quality. Analyzing the relationship between the planning process and ecosystem service flow from urban vegetation is fundamental for sustainable urban planning because it sets up a diachronic evaluation of the consequence of urbanization and new planning projects on human well-being.

Species differences of pollution removal are accounted for through differences in leaf surface area. However, the model does not differentiate removal effects among species on a per leaf area basis. That is, one square meter of leaf area is treated the same among all species in terms of removal rates per unit leaf area as there is not enough information to adequately separate individual species effects at the per unit leaf level. Other i-Tree models

Table 5

Distribution of species effect by dominance in leaf area.

Land use	Species	Leaf area (km ²)	Percent of air pollution removal (%)
Agriculture	London plane	0.59	21.79
	Horsechestnut	0.42	15.71
	Total (all species)	2.70	
Forest	European beech	11.15	21.62
	European ash	8.66	16.80
	English oak	5.96	11.56
	Total (all species)	51.56	
	Norway maple	1.24	24.78
Institutional	Japanese pagoda tree	0.62	11.87
	Crimean linden	0.59	11.20
	Total (all species)	5.22	
	Bigleaf linden	0.71	21.55
Industrial	Cedar of lebanon	0.69	20.83
	Greenspire linden	0.37	11.26
	Total (all species)	3.29	
	Sycamore maple	2.26	8.72
Park	European beech	2.17	8.37
	European ash	1.79	6.93
	Total (all species)	25.87	
	Silver linden	0.12	11.86
Residential	London plane	0.11	10.67
	Horsechestnut	0.11	11.27
	Total (all species)	1	
	White willow	0.08	23.24
Vacant	London plane	0.04	12.54
	Total (all species)	0.33	
	European ash	0.67	86.04
Water	Sycamore maple	0.08	9.86
	Total (all species)	0.78	
Total area		90.76	

use individual species characteristics to estimate which species are best for removing air pollution (e.g., Nowak, 2000).

The European beech (*Fagus sylvatica*), which is the most dominant species of municipal urban forest in Strasbourg, is considered as one of the top-rated species for removing the ozone and the carbon monoxide. Other species in Strasbourg are also estimated as important for reducing (i) particulate matter: black walnut (*Juglans nigra*); and (ii) carbon monoxide: ginkgo (*Ginkgo biloba*), Crimean linden (*Tilia euchlora*), tulip tree (*Liriodendron tulipifera*), silver linden (*Tilia tomentosa*) (Nowak, 2000). More research is needed to understand differing species abilities to remove air pollution (e.g., Beckett et al., 2000; Yang et al., 2015). This research will help in providing better recommendations to managers regarding selecting trees species to improve air quality. To encourage a sustainable urban forest management, managers could consider species with different characteristics such as sensitivity to pollution, adaptation to site, maintenance needs, etc. (Nowak, 2000). In addition to species selection, managers could adapt other techniques to enhance air pollution reduction by vegetation: sustain existing tree cover and healthy trees; use shrub edge in street canyon and next to road network to prevent the accumulation of air pollutant and accelerate their dispersion (Wania et al., 2012).

To improve on the first-order estimate in this paper, air pollution removal by urban trees in Strasbourg city need further research considering the associated complex ecological process and functions. Results of this study highlight the impact of trees on the atmosphere at the city scale and help local planners and managers understand local tree resources. However, pollution can also affect plant health and functions. For example, ozone is considered harmful to plants as it affects tree growth, photosynthesis and accelerates the senescence of leaves (Ashmore, 2005; Anav et al., 2012). The response of plant to ozone depends on other factors at a global/regional scale like the external concentration of ozone and the precursor pollutants emissions (NO_x and volatile organic compounds) (Ashmore, 2005; Al Madhoun and Rashid, 2014). Several studies have assessed or reviewed ozone effects on vegetation

in natural ecosystems (e.g., Felzer et al., 2004; Paoletti, 2006; Anav et al., 2011; de Vries et al., 2014). However, ozone impacts on urban trees remain to be investigated.

In Strasbourg, the ozone removal by trees was the highest among all studied air pollutants. This relatively high ozone removal is common (e.g., Nowak et al., 2006, 2014) due to the relatively high deposition velocities for ozone and the often high local ozone concentrations in cities. As trees are affected by ozone, research is needed to investigate if typical urban ozone concentration will have negative effects on air pollution removal by urban trees. Therefore, studying the feedback between urban vegetation and atmospheric chemistry by choosing a long-term and regional/municipal monitoring protocol could help scientists and planners to (i) better understand the interactions between biotic and abiotic components within urban context, (ii) develop adequate actions and tools for sustainable urban forest management and (iii) determine the extent of these action according to a spatial and temporal scale.

The i-Tree model provides relevant information about urban trees and its impact on urban environment that could serve both scientist and managers. Based on local data and field data, it reveals the link between tree structure and ecosystem services. The study of the architecture of the model shows that it articulates different numerical models including the dry deposition model highlighted in this paper. Therefore, it initiates an interdisciplinary approach to understand ecosystem services provided by urban trees. Nevertheless, model results have degrees of uncertainties that are linked to data inputs and model processes (e.g., uncertainties derived from the complexity of the physical and chemical processes involved in the trees-atmosphere interactions). The variety of input data required by the model represents both an asset and a source of uncertainties. For instance, map databases refer to different dates and different methodologies: the land use database is generated at 1:10000 scale; it is less detailed than SERTIT database which is referred to a finer scale (1:2000) and may produce inaccuracies when merging data. Additionally, the green spaces database

does not include the totality of street trees, which may lead to an underestimation of tree cover and thus air pollution removal.

Although the model was initially developed for US cities, i-Tree can be used worldwide, but requires data collection, input and formatting prior to use (e.g., Yang et al., 2005; Rogers et al., 2011; Morani et al., 2014; Baro et al., 2014). i-Tree Eco is now set to work in the U.S., Canada, Australia and the U.K. To apply i-Tree in other areas, users need to provide additional information regarding study location, new species (if encountered), and local weather and air pollution data. For required and desired data to use the model in non-American cities, along with model limitations, see the i-Tree Eco website (<https://www.itreetools.org/eco/international.php>).

While efforts are made to enhance the model functionalities, its adoption in France or other countries can be enhanced with additional research regarding tree species parameters (e.g., tree biomass, leaf area, growth rates). Baro et al. (2014) and Yang et al. (2005) suggest that uncertainties are also due to several factors like particle re-suspension rate, the spatial distribution of air pollutants, transpiration rates, meteorological conditions, etc. The model cannot estimate air pollution removal at small scale (street canyon scale, neighborhood scale, etc.), because it cannot take into account spatial and temporal variability of air pollutant concentration due to limited data on pollution concentrations at this scale (Hirabayashi et al., 2012). The model assesses average of air pollution removal based on measured tree data and average air pollution concentration across the city. Model parameters are adjusted depending on local collected tree data and locally measured meteorological and air pollution data. All these Model limitations can be minimized with better and more local input data (e.g., pollution concentration and weather data) and further research to improve tree species parameters and atmospheric exchanges with air pollution. Model results represent an initial approximation rather than a completely accurate valuation of air pollution removal. These approximations could help managers to understand the potential of urban trees in reducing air pollution at the city scale and could define new management and planning strategies to sustain and to promote cleaner air in cities using urban vegetation.

5. Conclusion

Modeling air pollution removal reveals the magnitude of tree effects on improving urban air quality. The effects of public trees in Strasbourg are relatively small with less than one percent air quality improvement, but depending upon the pollutant, this small percent have substantial health impacts for local residents (e.g., Nowak et al., 2014). The removal of 88 t of pollution per year by public trees can improve air quality and offset local emissions. However, the change in local air quality is not equally distributed and even though overall pollutant concentration is reduced, it can be increased at the local scale depending on urban forest and street design and local roadside emissions (Wania et al., 2012; Vos et al., 2013). Urban planners need to consider the impact of urban tree and green spaces on local air quality to create better and more informed plans that ensure air purification and sustain human health in cities.

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References

- ADEUS, 2015. Le Projet d'aménagement et de Développement durables, Retrieved April 21st, 2016 from <http://www.strasbourg.eu/developpement-rayonnement/urbanisme-logement-amenagement/planification-territoriale/plu/padd>.
- Al Madhoun, W.A., Rashid, M., 2014. An overview on the mutual relationship between forests and air pollution – gain and loss. In: *Proceeding of the National Conference Royal Belum, Gerik Perak, Malaysia*.
- Anav, A., Menut, L., Khvorostyanov, D., Viovy, N., 2011. Impact of tropospheric ozone on the Euro-Mediterranean vegetation. *Global Change Biol.* 17, 2342–2359.
- Anav, A., Menut, L., Khvorostyanov, D., Viovy, N., 2012. A comparison of two canopy conductance parameterizations to quantify the interactions between surface ozone and vegetation over Europe. *J. Geophys. Res.* 17, 1–20.
- Angelo, J., Andrade, L., Madeira, L.M., Mendes, A., 2013. An overview of photocatalysis phenomena applied to NO_x abatement. *J. Environ. Manage.* 129, 522–539.
- Ashmore, M.R., 2005. Assessing the future global impacts of ozone on vegetation. *Plant Cell Environ.* 28, 949–964.
- ASPA, 2014a. Urbanisme et exposition à la pollution atmosphérique, Retrieved April 21st, 2016 from http://www.atmo-alsace.net/medias/produits/Urbanisme_et_exposition.pdf.
- ASPA, 2014b. Consommations d'énergie et émissions atmosphériques en Alsace, Retrieved April 21st, 2016 from http://www.atmo-alsace.net/medias/produits/Consommations_energie_1.pdf.
- Baldocchi, D.D., Hicks, B.B., Camara, P., 1987. A canopy stomatal resistance model for gaseous deposition to vegetated surfaces. *Atmos. Environ.* 21, 91–101.
- Baldocchi, D., 1988. A multi-layer model for estimating sulfur dioxide deposition to a deciduous oak forest canopy. *Atmos. Environ.* 22, 869–884.
- Baro, F., Chaparro, L., Gomez-Baggethun, E., Langemeyer, J., Nowak, D.J., Terradas, J., 2014. Contribution of ecosystem services to air quality and climate change mitigation policies: the case of urban forests in Barcelona, Spain. *AMBIO* 43, 466–479.
- Beckett, K.P., Freer-Smith, P., Taylor, G., 2000. Effective tree species for local air quality management. *J. Arboric.* 26, 12–19.
- Bolund, P., Hunhammar, S., 1999. Ecosystem services in urban areas. *Ecol. Econ.* 293–301.
- Boonen, E., Beeldens, A., 2013. Recent photocatalytic applications for air purification in Belgium. *Coating* 4, 553–573.
- Boonen, E., Akyas, V., Barmpas, F., Boréave, A., Botallico, L., Cazaunau, M., Chen, H., Daële, V., De Marco, T., Doussin, J.F., Gaimoz, C., Gallus, M., George, C., Grand, N., Grosselin, B., Guerrini, G.L., Herrmann, H., Ifang, S., Kleffmann, J., Kurtenbach, R., Maille, M., Manganello, G., Mellouki, A., Miet, K., Mothes, F., Moussiopoulos, N., Poulain, L., Rabe, R., Zapf, P., Beeldens, A., 2015. Construction of a photocatalytic De-polluting field site in the Leopold II tunnel in Brussels. *J. Environ. Manage.* 155, 136–144.
- Brunekreef, B., Holgate, S.T., 2002. Air pollution and health. *Lancet* 360, 1233–1242.
- Cavanagh, J.E., 2006. Potential of Vegetation to Mitigate Road-generated Air Pollution, Retrieved April 21st, 2016 from <https://www.niwa.co.nz/sites/niwa.co.nz/files/import/attachments/co1x0405.p05.pdf>.
- Chaparro, L., Terradas, J., 2009. Ecological Services of Urban Forest in Barcelona, Retrieved April 21st, 2016 from <http://www.itreetools.org/resources/reports/Barcelona%20Ecosystem%20Analysis.pdf>.
- Chatignoux, E., Host, S., 2013. Expositions à la pollution atmosphérique et recours aux urgences pour pathologies respiratoires chez les enfants en Ile-de-France, Retrieved April 21st, 2016 from http://www.ors-idf.org/images%5Cbook_file%5C2013SyntheseErpurs2013.pdf.
- Chen, J., Poon, C.S., 2009. Photocatalytic construction and building materials: from fundamentals to applications. *Build. Environ.* 44, 1899–1906.
- Cherlin, N., Roustan, Y., Mousson-Genon, L., Seigneur, C., 2015. Modelling atmospheric dry deposition in urban areas using an urban canopy approach. *Geosci. Model Dev.* 8, 893–910.
- Citeair, 2011. Integrated Urban Emission Inventories, Retrieved April 21st, 2016 from http://www.citeair.eu/fileadmin/Deliverables_and_documents/Guidebook.Integrated.Emission.Inventories.-final.pdf.
- Colbeck, I., Harrison, R.M., 1985. Dry deposition of ozone: some measurements of deposition velocity and of vertical profiles to 100 m. *Atmos. Environ.* 19, 1807–1818.
- Currie, A.B., Bass, B., 2008. Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. *Urban Ecosyst.* 11, 409–422.
- EMS, 2013. Les forêts rhénanes de Strasbourg, Retrieved April 21st, 2016 from <http://www.strasbourg.eu/environnement-qualite-de-vie/foret-reserves-naturelles/forets-rhenanes-strasbourgeoises>.
- de Vries, W., Dobbertin, M.H., Solberg, S., van Dobben, H.F., Schaub, M., 2014. Impacts of acid deposition, ozone exposure and weather conditions on forest ecosystems in Europe: an overview. *Plant Soil* 380, 1–45.
- EEA, 2009. The EMEP/EEA Air Pollutant Emission Inventory Guidebook, Retrieved April 21st, 2016 from <http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009>.
- EEA, 2014a. Air Quality in Europe, Retrieved April 21st, 2016 from <http://www.eea.europa.eu/publications/air-quality-in-europe-2014>.
- EEA, 2014b. France air pollution fact sheet, Retrieved May 1st, 2016 from <http://www.eea.europa.eu/themes/air/air-pollution-country-fact-sheets-2014/france-air-pollutant-emissions-country-factsheet/view>.

- Escobedo, F., Kroeger, T., Wagner, J., 2011. Urban forests and pollution mitigation: analyzing ecosystem services and disservices. *Environ. Pollut.* 159, 2078–2087.
- Felzer, B., Kicklighter, D., Melillo, J., Wang, C., Zhuang, Q., Prinn, R., 2004. Effects of ozone on net primary production and carbon sequestration in the conterminous United States using a biogeochemistry model. *Tellus* 56, 230–248.
- Froger, G., Méral Ph, Le Coq, J.F., Aznar, O., Boisvert, V., Caron, A., Antona, M., 2012. Regards croisés de l'économie sur les services écosystémiques et environnementaux. *Vertigo* – la revue électronique en sciences de l'environnement 12, Retrieved April 21st, 2016 from <http://vertigo.revues.org/12900>.
- Gromke, C., Ruck, B., 2009. On the impact of trees on dispersion processes of traffic emissions in street canyons. *Boundary Layer Meteorol.* 131, 19–34.
- Heinrich, J., Wichmann, H.E., 2004. Traffic related pollutants in Europe and their effect on allergic disease. *Curr. Opin. Allergy Clin. Immunol.* 4, 341–348.
- Hirabayashi, S., Kroll, C.N., Nowak, D.J., 2011. Component-based development and sensitivity analyses of an air pollutant dry deposition model. *Environ. Modell. Software* 26, 804–816.
- Hirabayashi, S., Kroll, C.N., Nowak, D.J., 2012. Development of a distributed air pollutant dry deposition modeling framework. *Environ. Pollut.* 171, 9–17.
- Hirabayashi, S., Kroll, C.N., Nowak, D.J., 2015. i-Tree Eco Dry Deposition Model Descriptions, Retrieved April 21st, 2016 from <https://www.itreetools.org/ecodescription/iTreeEcoDryDepositionModelDescriptions.pdf>.
- Hosker Jr., R.P., Lindberg, S.E., 1982. Review: atmospheric deposition and plant assimilation of gases and particles. *Atmos. Environ.* 16, 889–910.
- i-Tree Eco User's Manual, 2013, Retrieved January 23rd, 2013 from <https://www.itreetools.org/resources/manuals/Eco.Manual.v5.pdf>: <http://www.itreetools.org/resources/archives>.
- Jagielski, K.D., O'Brien, R.J., 1994. Calculation Methods for Criteria Air Pollutant Emission Inventories, Retrieved April 21st, 2016 from <http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA284675>.
- Lovett, G.M., 1994. Atmospheric deposition of nutrients and pollutants in North America: an ecological perspective. *Ecol. Appl.* 4, 629–650.
- Morani, A., Nowak, D.J., Hirabayashi, S., Guidolotti, G., Medori, M., Muzzini, V., Fares, S., Scarascia Mugnozza, G., Calfapietra, C., 2014. Comparing i-Tree modeled ozone deposition with field measurements in a periurban Mediterranean forest. *Environ. Pollut.* 195, 202–209.
- NOAA, 2016, website: <http://www.ncdc.noaa.gov/cdo-web/>.
- 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 Ecosystem: Results of the Chicago Urban Forest Climate Project*, Gen Tech. Rep. NE-186. USDA Forest Service, Radnor, PA, pp. 63–81.
- Nowak, D.J., 2000. Tree species selection, design, and management to improve air quality. *Construction Technology: Annual Meeting Proceedings of the American Society of Landscape Architects*.
- Nowak, D.J., Crane D.E., The Urban Forest Effects (UFORE) Model: quantifying urban forest structure and functions. In: Hansen M., Burk T. (Eds.), *Integrated tools for natural resources inventories in the 21st century: proceedings of the IUFRO conference*, Gen. Tech. Rep. NC-212, St. Paul, 714–720, 2000.
- Nowak, D.J., Crane, D.E., Stevens, J.C., Ibarra, M., 2002a. *Brooklyn's Urban Forest General Technical Report NE- 290*. USDA Forest service, Newtown Square, PA.
- Nowak, D.J., Stevens, J.C., Sisinni, S.M., Luley, C.J., 2002b. Effects of urban tree management and species selection on atmospheric carbon dioxide. *J. Arboric.* 28, 113–122.
- Nowak, D.J., Crane, D.E., Stevens, J.C., 2006. Air pollution removal by urban trees and shrubs in the United States. *Urban For. Urban Greening* 4, 115–123.
- Nowak, D.J., Walton, J.T., Stevens, J.C., Crane, D.E., Hoehn, R.E., 2008. Effect of plot and sample size on timing and precision of urban forest assessments. *Arboric. Urban For.* 34, 386–390.
- Nowak, D.J., Hirabayashi, S., Bodine, A., Hoehn, R., 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., Hirabayashi, S., Bodine, A., Greenfield, E., 2014. Tree and forest effects on air quality and human health in the United States. *Environ. Pollut.* 193, 119–129.
- Owen, S.M., Mackenzie, A.R., Stewart, H., Donovan, R., Hewitt, C.N., 2003. Biogenic volatile organic compound (VOC) emission estimates from an urban tree canopy. *Ecol. Appl.* 13, 927–938.
- Paoletti, E., 2006. Impact of ozone on Mediterranean forests: a review. *Environ. Pollut.* 144, 463–474.
- Paoletti, E., Bardelli, T., Giovannini, G., Pecchioli, L., 2010. Air quality impact of an urban park over time. *Procedia Environ. Sci.* 4, 10–16.
- Rogers, K., Jarrat, T., Hansford, D., 2011. Torbay's Urban Forest: Assessing Urban Forest Effects and Values, Retrieved April 21st, 2016 from http://www.itreetools.org/resources/reports/Torbay_UF_Report.pdf.
- Roupsard, P., 2013. Etude Phénoménologique Du dépôt Sec d'aérosols En Milieu Urbain. Ph.D Thesis. University of Rouen.
- Rückerl, R., Schneider, A., Breitner, S., Cyrys, J., Peters, A., 2011. Health effects of particulate air pollution – a review of epidemiological evidence. *Inhal. Toxicol.* 23, 555–592.
- Salmond, J.A., Williams, D.E., Laing, G., Kingham, S., Dirks, K., Longley, I., Henshaw, G.S., 2013. The influence of vegetation on the horizontal and vertical distribution of pollutants in a street canyon. *Sci. Total Environ.* 443, 287–298.
- Schlesinger, R.B., 1979. Natural removal mechanisms for chemical pollutants in the environment. *Bioscience* 29, 95–101.
- Selmi, W., 2014. Évaluation Des Services écosystémiques Rendus Par La végétation Urbaine. Application d'approches d'évaluations À La Ville De Strasbourg. Ph.D Thesis. University of Strasbourg.
- Sénat, 2015. Coût économique et financier de la pollution de l'air, Retrieved April 21st, 2016 from <http://www.senat.fr/rap/r14-610-1/r14-610-11.pdf>.
- Taylor Jr., G.E., Hanson, P.J., Baldocchi, D.D., 1988. Pollutant deposition to individual leaves and plant canopies: sites of regulation and relationship to injury. In: Heck, W.W., Taylor, O.C., Tingey, D.T. (Eds.), *Assessment of Crop Loss from Air Pollutants*. Elsevier Applied Science London, England, pp. 227–258.
- Tiwary, A., Kumar, P., 2014. Impact evaluation of green-grey infrastructure interaction on built-space integrity: an emerging perspective to urban ecosystem services. *Sci. Total Environ.* 487, 350–360.
- UNEP, 2014. Les villes les plus vertes de France, Palmares 2010, dossier de presse, Retrieved April 21st, 2016 from <http://www.entreprisesdupaysage.org/espace-presse/dossiers-de-presse-unep/614-palmares-des-villes-les-plus-vertes-de-france-decouvrez-les-resultats->.
- Vos, P., Maiheu, B., Vankerkom, J., Janssen, S., 2013. Improving local air quality in cities: to tree or not to tree? *Environ. Pollut.* 18, 113–122.
- Wania, A., Bruse, M., Blond, N., Weber, C., 2012. Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations. *J. Environ. Manage.* 94, 91–101.
- Wesely, M.L., 1989. Parameterization of surface resistances to gaseous dry deposition in regional-scale numerical models. *Atmos. Environ.* 23, 1293–1304.
- WHO, 2006. Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide. WHO, Denmark, pp. 484 p.
- Yang, J., McBride, J., Zhou, J., Sun, Z., 2005. The urban forest in Beijing and its role in air pollution reduction. *Urban For. Urban Greening* 3, 65–78.
- Yang, J., Chang, Y., Yan, P., 2015. Ranking the suitability of common urban tree species for controlling PM_{2.5} pollution. *Atmos. Pollut. Res.* 6, 267–277.
- Young, R.F., 2010. Managing municipal green space for ecosystem services. *Urban For. Urban Greening* 9, 313–321.