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$PM_{2.5}$ Dry deposition on vegetation and application on green interventions in Autostrada Regionale Cispadana

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Abstract:

Problems related to a high concentration of $PM_{2.5}$ within the atmosphere are becoming an object of interest by the international community and the public administration increasingly for the adverse health effects linked to humans. Its size gives it a high capacity for penetration with the lung system. It is therefore essential to study atmospheric removal processes. This work focused on the deposition processes of the atmospheric $PM_{2.5}$ on vegetation through phenomena that occur continuously over time as dry deposition, not due to atmospheric precipitation. The air passing inside the vegetation allows the particles to settle through impact, interception, and Brownian motions. The characteristics of the foliar surface are decisive in its effective removal of $PM_{2.5}$; as the roughness increases deposition, the presence of waxes and down on the foliar layer also increase the retention capacity. The species that most succeed in intercepting the $PM_{2.5}$ are the conifers, which, compared to deciduous species, do not suffer the loss of the leaves during the autumn season and are covered by a layer of wax.

Several types of models quantify the deposition of $PM_{2.5}$ on plant surfaces, including "I-Tree", the ENVI-MET model, and an extension of ArcviewGIS, called CITY-green. ENVI-MET is a CFD model that allows the analysis of the dispersion of particles caused by vegetation; City green instead performs its assessments based on a database containing characteristics of plant species used in the GIS system. I-Tree is chosen here because it is the model that is more widespread at the national and international level for this type of operation, given its ease of use. The latter starting from the sampling of the structural characteristics of the vegetation, the concentration of PM2.5 in the air and atmospheric data, can quantify the amount of PM2.5 removed from the vegetation each year.

The “Regional Cispadana Motorway” construction is planned shortly, which will connect the A22 Modena-Brenno with the A13 Bologna Padova, following a west-east route. This work was designed to plant vegetation for mitigating purposes, both landscape (masking of the work, ornamental interventions…) and atmospheric (function of mitigation of air). The objective of the case study is to quantify the amount of PM2.5 removed from both types of interventions. To do so, the software “I-Tree planting Calculator” was used here. The total emission of the work is estimated at 48403.8 kg PM2.5 /year. Thanks to its particulate capture capacity, the vegetation allows an overall decrease of 652.2 kg $PM_{2.5}$/year, equal to 1.3% of total emissions. Future studies should focus on finding out more about the phenomena affecting the dry deposition of $PM_{2.5}$ on vegetation to increase the effectiveness of mitigation interventions.

Abstract (Italian Version):

Le problematiche legate ad un’alta concentrazione di $PM_{2.5}$ all’interno dell’atmosfera stanno diventando sempre più oggetto di interesse da parte dalla comunità internazionale e dalla amministrazione pubblica, per gli effetti negativi sulla salute legati sia alla sua composizione che comprende sostanze dannose per l’uomo, che per le sue dimensioni le conferiscono un’alta capacità di penetrazione all’interno del sistema polmonare. È importante quindi studiarne i processi di rimozione atmosferica. In questo lavoro, ci si è soffermati sui processi di deposizione del $PM_{2.5}$ atmosferico sulla vegetazione, attraverso fenomeni che avvengono continuativamente nel tempo come la deposizione secca, non dovuta alle precipitazioni atmosferiche. L’aria passando all’interno della vegetazione permette alle particelle di depositarsi su di essa, attraverso meccanismi come: impatto, intercettamento e moti browniani. Le caratteristiche della superfice fogliare sono determinanti nella sua efficacia rimozione di rimozione del PM2.5, all’aumentare della rugosità aumenta la deposizione, la presenza di cere e peluria sullo strato fogliare aumentano anch’esse la capacità di ritenzione. Le specie che maggiormente riescono ad intercettare il $PM_{2.5}$ sono le conifere, le quali rispetto alle specie caducifoglie, non subiscono la perdita delle foglie durante la stagione autunnale e sono ricoperte da uno strato di cera.

In commercio esistono diverse tipologie di modelli che quantificano la deposizione di $PM_{2.5}$ sulle superfici vegetali, tra cui: “i-Tree”, il modello ENVI-MET e, un’estensione di ArcViewGIS, chiamata CITY-green. ENVI-MET è un modello CFD che consente l’analisi della dispersione delle particelle causata dalla presenza della vegetazione, CITYgreen invece esegue le proprie valutazioni basandosi su un database contenente caratteristiche di specie vegetali utilizzate nel sistema GIS. I-Tree viene qui scelto in quanto è il modello che per questa tipologia di operazioni è maggiormente diffuso a livello nazionale e internazionale data la sua semplicità di utilizzo. Quest’ultimo partendo dal campionamento delle caratteristiche strutturali della vegetazione, dalla concentrazione di $PM_{2.5}$ nell’aria e dati atmosferici riesce a quantificare il quantitativo di $PM_{2.5}$ rimosso dalla vegetazione ogni anno.

È prevista a breve la realizzazione dell’“Autostrada regionale Cispadana”, che seguendo una direttrice ovest-est metterà in collegamento l’A22 Modena-Brennero, con l’autostrada A13 Bologna-Padova. Per tale opera è stata prevista la piantumazione di vegetazione a scopi mitigativi sia paesaggistici (mascheramento dell’opera, interventi ornamentali…) che atmosferici (funzione di mitigazione dell’aria), l’obiettivo del caso studio è quantificare il quantitativo di $PM_{2.5}$ rimosso da entrambe le tipologie di interventi, per fare ciò il software “i-Tree planting Calculator” è stato qui utilizzato. L’emissione totale dell’opera è stimata in 48403.8 kg $PM_{2.5}$/anno mentre grazie alla sua capacità di cattura del particolato la vegetazione consente una diminuzione complessiva di 652.2 kg $PM_{2.5}$/anno pari all’ 1.3% delle emissioni totali. Studi futuri dovranno concentrarsi sulla ricerca di una maggiore cognizione dei fenomeni che influenzano la deposizione secca del $PM_{2.5}$ sulla vegetazione al fine di aumentare l’efficacia degli interventi mitigativi.

Summary

1 INTRODUCTION

With the rapid development of urbanization and industrialization, environmental pollution has become a common problem. Particulate pollution is a severe concern in developed countries, especially in urban and suburban areas. It has adverse effects on human health, exacerbating a wide range of respiratory and vascular illnesses. Among the pollution types, particulate pollution, notably PM_{10} and $PM_{2.5,}$ affect human health. The notably particular matter having an aerodynamic diameter <2.5 µm ($PM_{2.5}$) can cause serious harm to human health and represents the most dangerous fraction. It is therefore becoming increasingly important to found remedies to reduce the concentration of $PM_{2.5}$.

One of the most readily practical solutions by the public administrations is to exploit the capacity of the vegetation to facilitate the deposition of $PM_{2.5}$, particularly the dry one that happens uninterruptedly over time and does not depend on the atmospheric precipitation. This thesis aims to understand the phenomenon of dry deposition of $PM_{2.5}$ on vegetation and its factors. It will identify and test the most suitable model to quantify this phenomenon, trying to grasp the operation and limitations of the model itself.

In the introductory part, a description of $PM_{2.5}$, its chemical composition, and its sources, followed in paragraph 2.3, illustrated the mechanisms that make up the dry deposition at a microscopic level (Brownian motions, interception, impact). The primary parameter with which the phenomenon is quantified is the deposition rate of particles, and this parameter has been illustrated along with other collateral phenomena such as resuspension. In paragraph 2.5, vegetation influences deposition through its microscopic characteristics (roughness, waxy coatings, shape of leaves, leaf hairs) and macroscopic (tree structure, branch diameter). Also, the meteorological conditions (wind speed, temperature, humidity) influence the deposition rate. Other phenomena such as particle resuspension and wash-off have their influence. Once deposited on the foliar surface, these particles migrate to different environmental matrices, thanks to the two previous phenomena. The chapter concludes with an example of PAHs transport and a description of the urban forest concept.

Chapter 3 opens with a brief description of what are three most used models in the world according to the study carried out by (Nowak, et al., 2019), which analyzes thousands of scientific publications on the subject noted as “I-Tree Eco”, “ENVI-MET” and “Citygreen” are the most exciting applications. In particular, the widely used one is i-Tree Eco and is therefore chosen as a reference model in this thesis work. In particular, the light version of the latter was used, namely the application “i-Tree Planting Calculator”, which is nothing more than a user-friendly and more usable interface of i-Tree Eco but which is based on the structure and calculations of the latter. Below, the i-Tree Eco model is analysed in detail, describing its history, its origin, and the mathematical formulas on which it bases its calculations. In section 3.6, the main theoretical limits of i-Tree Eco have been explained (differences between real and input data, lack of input data, etc..), basing their observations on specific studies of the limits of the model.

In chapter 4, there is a case study in which the i-Tree Planting Calculator software was applied. In 2021 work is planned to construct the regional motorway Cispadana, in the north of Emilia, which will connect the “A22-Modena Brennero” with the A13 “Bologna-Padova”. The project has provided for the implementation of vegetation along the highway's entire route to mitigate the effects produced by the work itself, whether aesthetic (masking of the work, etc.) or environmental (capture of air pollutants in highly trafficked areas).

The purpose of the case study is to assess the amount of $PM_{2.5}$ removed annually from the interventions specially prepared, and those created for other purposes and compare it with the emissions produced by the work. The software i-Tree Planting Calculator is based on data relating to US Territory. Therefore, necessary to search for a geographical area in the United States that was meteorologically similar and had the same concentrations of $PM_{2.5}$ as the areas crossed from the highway. The same concept has been applied to the plant species included in the software resulting from a comparison work between the species present in the Highway project. Sensitivity analyses of the different input parameters of the software have been carried out, and other scenarios have been analysed. The case study will allow having practical feedback on the type of results obtained with this type of software. Moreover, it will afford to understand as the theoretical phenomena represented in this thesis job have feedback on the final result.

2 DEPOSITION PROCESS

$PM_{2.5}$ is analysed in the introductory part of this chapter. The $PM_{2.5}$ present inside the aeriform currents is deposited on all types of surfaces, among which the most interesting is undoubtedly the vegetal ones. The urban forest represents most of the vegetal surfaces of the urban contexts. In this chapter, a definition is given that turns out helpful in successive passages of this thesis work. Among the deposition mechanisms, dry deposition on vegetation is examined in more detail, as well as the phenomenon of re-suspension of particles that meet the foliar surface, deepening the factors that most affect the dry deposition and the micro and macroscopic characteristics of the vegetation that have a greater weight on the deposit.

A list of tree and plant species with a greater capacity than other species to catch and retain $PM_{2.5}$ on their foliar surface is provided. The meteorological variables (wind speed, temperature, and humidity) are related to the deposition rate values. In the final part, a brief note is made of the transport of contaminants from the foliar surface to the other environmental matrices, using the example of PAHs.

2.1 Atmospheric particulate matter

Atmospheric particulate matter (PM) is generally defined as a mixture of solid and/or liquid particles suspended in the air. Atmospheric PM can be emitted from various sources that affect its physical properties (size, surface, density), chemical composition, and dimensional distribution. PM can be classified as primary or secondary according to its formation mechanism: primary particles are emitted directly into the atmosphere, while secondary particles are formed after the chemical transformation of their gas precursors. Atmospheric particulate matter includes particles with dimensions ranging from a few manometers to several hundred micrometres. Generally, it is divided into four size fractions according to the PM aerodynamic diameter (D_p), including total suspended particles (TSP; D_p<100µm), coarse particulates (PM_{10} 2.5<D_P<10µm), fine particles ($PM_{2.5}$; Dp<2.5µm) and ultrafine particles (UFPs, $PM_{0.1}$; Dp<0.1 µm).

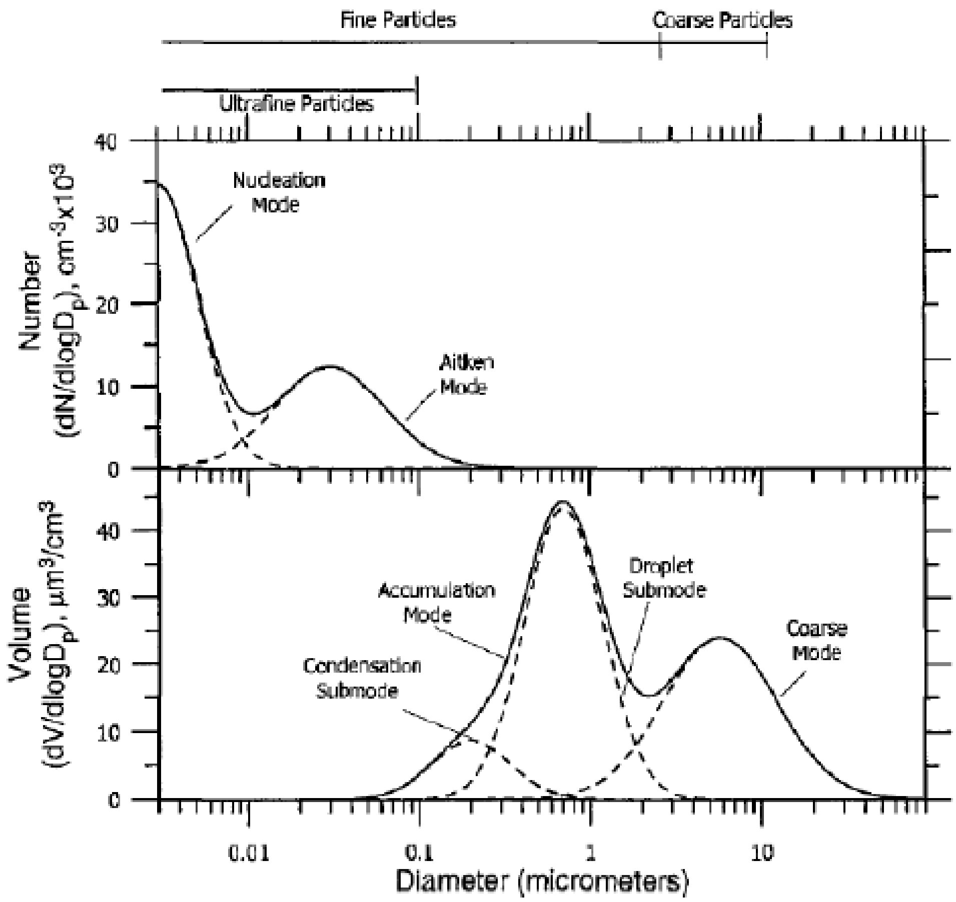

Figure 2-1Typical particulate distribution in number (above) and volume (below).

The volume distribution by assuming constant particle density can be seen as a mass distribution: this is characterized by two fads, the “accumulation mode” and the “coarse mode”. The coarse mode consists of the particle with a diameter of between 2µm and 50µm, generally produced by mechanical processes such as wind or erosion (mineral, dust, pollen, sea salt). However, there may be secondary compounds such as nitrates and sulphates. The accumulation trend from (0.1 to 2µm) is linked to primary emissions, the condensation of sulphates, nitrates and secondary organic compounds, and smaller particles' coagulation. The accumulation mode is the result of two superimposed sub-modes: the “condensation submode”, formed by primary emissions of particulate matter, growth of smaller particles by coagulation and condensation of steam, and the “droplet submode”, created by particle agglomerations of the “Aitken cores” due to collision between the cores due to thermal agitation.

2.1.1 Chemical composition

The chemical composition of atmospheric particulates varies greatly both on a temporal and spatial scale and depends on numerous factors: the most important is the chemical composition of the area of origin, the nature of the primary sources and the distance from them. Typical PM compositions include natural crustal materials (carbonates, silicates), inorganic constituents such as sulphate, nitrate, sodium, potassium, chloride and ammonium, TMs, and organic components. The aerosol sources of metals are dominated by desert dust (mineral aerosols) for Al, Ti, Mn and Fe. Still, combustion sources might also contribute to them and may be especially important for Cu, Zn, Pb, while Metals may dominate Cd sources.

The main elements of particulate matter in the atmosphere are usually inorganic ions, especially nitrates, sulphates and ammonia, mineral dust, sea salt and carbon aerosol. Carbon aerosol consists of elemental carbon (EC) and organic carbon (OC). The elemental carbon, also called "black carbon", graphite carbon or soot, is emitted directly into the atmosphere mainly by combustion processes that occur in the presence of sub-stoichiometric oxygen. Black carbon is characterized by the high absorption capacity of light radiation and is believed to be one of the substances contributing most to global climate change. Organic carbon, which can be either directly emitted or the result of condensation of low volatility organic gases, comprises mixtures of hundreds of organic compounds, including alkanes, aromatic hydrocarbons (PAHs) and BTEX (Benzene, Toluene, Ethylene benzene and Xylene).

The chemical speciation of particulates varies according to the size range considered: in the fine particles are mainly sulphates, ammonia, OC, EC, and some transition metals, such as nickel and zinc, while in the coarse fraction prevail iron, organic biogenic particles (pollen, spores, vegetation fragments) and elements of the earth's surface (silicon, calcium, magnesium, titanium, iron, and aluminium). Nitrates can be found both in the fine fraction, in the form of ammonium nitrate (NH_4NO_3) produced by the reaction between nitric acid (HNO_3) and ammonia (NH_3) and in the course one, as a result of the reactions between nitric acid and coarse particles.

2.1.2 Sources

Atmospheric particulate matter can be either of natural origin, generated mainly by low-temperature processes or anthropogenic origin, developed predominantly at high temperatures. The primary natural source of particulate matter globally is the ocean which emits sea salt or sprays for wind and waves. Other important natural emissive sources are the Earth's crust because of mechanical erosion processes, chemical and biological alteration and wind erosion, volcanic emissions, and forest fires. On the other hand, anthropogenic particulates derive mainly from industrial activities, the combustion of fossil fuels for domestic heating and energy production, the incineration of waste, the production of chemicals, and vehicular traffic.

The main precursor gases of PM are ammonia, nitrogen oxides (NOx), sulphur dioxide and volatile organic compounds, and their contribution is not negligible. For example, it is estimated that the emission of one tonne of nitrogen oxides results in the formation of 880 kg of PM_{10}. (Torresi, 2018) Due to a heterogeneous composition of different naturally occurring dust, it is often challenging to examine the effects of PM on the vegetation in specific experimental settings. (Ullrichs, et al., 2008).

2.2 Deposition processes

Depositions of atmospheric particles onto vegetation surface have three major routes:

1) Wet deposition
2) Dry deposition
3) Occult deposition obscured from measurements that determine wet and dry deposition by fog, cloud-water, and mist interception.

Dry deposition of atmospheric particles to plant and soil is a much slower process than wet or occult deposition, but it acts nearly continuously and affects all exposed surfaces.

2.3 Dry deposition on vegetation

The effect of vegetation on deposition depends primarily on the spatial scale of reference. The deposition of a particle on a plant is mainly influenced by the shape and structure of leaves or needles. Instead of considering the individual leaves, the sediment can be increased or reduced depending on the surface structure. Deposition means transport from a point in the air to an end on a surface. Dry deposition reduces the concentration of pollutants C_i through a first-order process:

$$\frac{dC_i}{dt} = -\frac{V_{d,i}}{z} \times C_i \qquad (1)$$

where z is the height at which the pollutant is well mixed, $V_{d,i}$ represents the deposition rate, which depends on the pollutant i and many other factors, including the nature of the surface on which the deposition occurs. Deposition velocity is a coefficient that considers the various processes involved in a deposition, including Brownian diffusion, interception, inertial impact, and sedimentation.

2.3.1 Brownian diffusion

Brownian diffusion is linked to Brownian motions; airborne particles in a fluid are continually "bombarded" by the surrounding molecules; this constant bombardment results ins a random motion of particles, called "Brownian motion". The phenomenon is related to the coefficient of Brownian diffusion D, equal to

$$D = \frac{k_B T Cc}{3\pi \mu_a D_P} \left(\frac{m^2}{s} \right) \tag{2}$$

Brownian motions concern particles with a diameter of less than 0.1µm. The factor that limits the deposition is the transfer through the boundary layer which surrounds the obstacle. For an isolated obstacle, the collection velocity V_b is related to the Sherwood number S_h through:

$$V_b = \frac{S_h D_B}{d_n} \tag{3}$$

where D_B is the Brownian diffusion coefficient d_n the dimension of the vegetation. (Petroff, et al., 2008).

2.3.2 Interception

An interception occurs when particles of small inertia, which perfectly follow the streamlines of the mean flow field, pass in the vicinity of an obstacle and are held back because the distance between the particle centre and the surface is smaller than half the diameter. The associated efficiency is mainly parametrised with theoretical results obtained in potential flow. Slinn (1982) adapts it to consider the interception that takes place both on the foliar surface, characterised by the diameter d_n, and on the micro-roughness's of the surface, characterised by a diameter d_r.

2.3.3 Impact

An aerosol particle transported by the flow towards an obstacle cannot; when its inertia is too large, follow the flow deviation in the vicinity of the obstacle. Thus, the particle collides with the obstacle surface and remains on its surface when particle rebound is ignored. The collection velocity or efficiency is classically related to the Stokes number.

$$S_t = \frac{V_S u_*}{gA} [-] \tag{4}$$

It remembers that a particle with a low Stokes number follows fluid streamlines. In contrast, a particle with a large Stokes number is dominated by its inertia and continues along its initial trajectory and can therefore more easily collides against the obstacle. The parameters e V_S e u_* represents respectively the sedimentation rate of the particle and the friction rate [m/s], the acceleration of gravity [m/s^2], A is related to the size of the collector [m] and varies according to plant species.

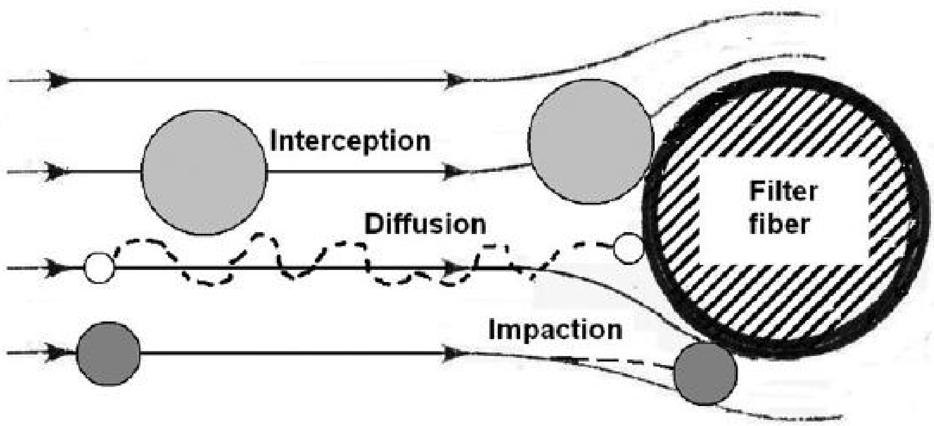

Figure 2-2 depositions type.

2.3.4 Velocity of sedimentation

Deposition velocity is one of the most critical parameters in this thesis work, it is. A substantial value for the assessment of the performance of dust filtration by the plant. Numerous studies have already demonstrated the importance of dry deposition in the removal of airborne pollutant particles, and deposition flux is described as :

$$F = V_d * C \ \left[\frac{(\mu g)}{(m^2 s)}\right] \qquad (5)$$

V_d is the deposition velocity [m/hr or cm/s] of particulate matter to a specific surface, which varies depending on surface roughness and surrounding environmental conditions. C is the concentration of atmospheric particulate matter in a specific area local environment [$\mu g/m^3$]. Therefore, V_d could be used as a direct determinant of the ability of plants to remove atmospheric particulate matter.

This thesis's primary issue was the need to directly measure concentrations of $PM_{2.5}$ retained on plant leaves under realistic environmental conditions. As the dust found on leaf surfaces is often a mixture of miscellaneous coarse and fine particles, accurate measurements of $PM_{2.5}$ concentration were difficult to distinguish. Thus, the Vd of particulate matter pollutants maintained on the surfaces of plant leaves were measured using the Empirical Formula and Wind Tunnel Test (Huang). The empirical formula method utilized a simplified one-dimensional depositional model to calculate the V_d of atmospheric pollutants Eq.6

$$V_d = \frac{1}{R_{tot}} = \frac{1}{R_a} + \frac{1}{R_b} + \frac{1}{R_c} \left[\frac{m}{s}\right] \qquad (6)$$

Vd is the reciprocal of resistance to deposition, $R_{tot,}$ which equals the sum of the reciprocal aerodynamic resistance *(R_a)*, boundary resistance *(R_b)*, and surface resistance (R_c) of each transport process, the resistance parameters of PM_{10}, SO_2, NO_2 and CO were found in existing literature or measured using the empirical formula. However, the empirical formula did not apply to the measurement of $PM_{2.5}$, and no significant parameter values were reported.

2.3.4.1 Variation of deposition velocity with a diameter

For particles with a diameter of d_p>10 µm, sedimentation by gravity is the crucial deposition process. Sedimentation is only significant up to a diameter of d_p>1 µm; the particle's mass and the acceleration due to gravity are reduced, decreasing the diameter. Minimum values of deposition rate are recorded for particle diameters between 0.1 and 1 µm. Impaction and interception are the main processes acting on particles in the air. Contributions to dry deposition from Brownian diffusion and sedimentation are negligible for particles with diameter d_p<0.1 µm, interception and impaction are less significant, as particle sizes fall below this value, inertia and deposition are also reduced. In this size class, the only diffusion is effective but still results in high deposition rates. Near to surfaces, particles are continuously deposited by Brownian motion resulting in a concentration gradient that induces a mass flow toward surfaces. For smaller diameters, the particle behaves, to a first approximation, as the gases and the Brownian diffusion represents an effective transport mechanism.

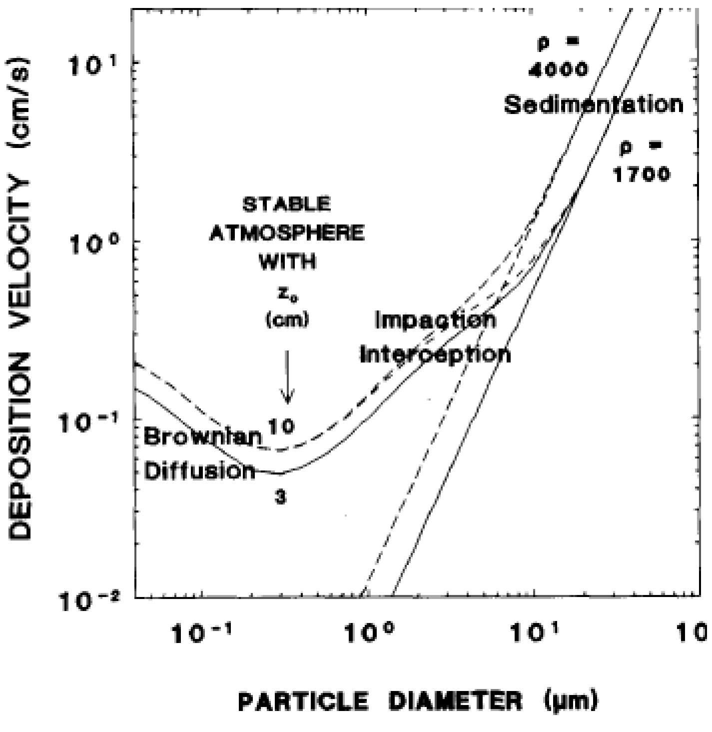

Figure 2-3 Typical curves for the deposition velocity of particles as a function of size in a stable atmosphere for two different roughness lengths (z_0 in cm) and particles densities (ρ in kgm^{-3}). The settling velocity of particles is also indicated. The curves were calculated with u=5 m/s using the model described by Sehmel and Hodgson.

2.4 Resuspension

Resuspension is closely tied to the speed of the wind. The mechanisms responsible for the resuspension of particles back into the air are three:

(i) Viscous, when the force of airflow is great enough to detach the particle.

(ii) Turbulent, in which energized turbulent air disrupts the boundary layer and lifts particles away into the airflow.

(iii) Detachment from vibration or shaking of the whole leaf.

The most active component of resuspension for particles < 2µm is (iii) the physical movement of the leaf. The resuspension and deposition rates varied with different sizes even if the wind speed was similar, i.e., large particles and coarse particulates were easily blown off, while fine particulate matter distributed in the grooves of leaf surface was not readily blown away.

Rebound

This phenomenon is thought to influence coarse particle deposition, with a size typically larger than 5µm. The deposition of coarse aerosols (20µm) is mainly controlled by the friction velocity and surface adhesion and is far less sensitive to vegetation surface roughness or morphology. From a mechanical point of view, the rebound is related to the kinetic energy of the incident particle, obtained from the particle velocity component normal to the deposit surface and the nature of the impact. Also, it depends possibly on adhesion conditions. Inversely, deposition of smaller particles (accumulation and Aitken modes) is strongly influenced by the canopy geometry properties and the balance between the various transport and collection processes. (Petroff, et al., 2008)

2.5 Factors affecting deposition.

$PM_{2.5}$ eventually settles onto surfaces of all kinds through dry deposition. Of the available surfaces on Earth, trees capture a higher proportion of particulate than other vegetation types because they allow the wind to move through them. In contrast, the high surface area of leaves will enable particles to fall out of the air and deposit. It must be said that the leaf accumulated large particles dominated PM, and the fine particles made up the minor proportion of the accumulated PM; on average, 90% del particulate matter deposited has a diameter larger than 10µm. (Wang, et al., 2015)

The effects of plant species on deposition depend on the size scale considered. Regarding the plant, deposition is mainly affected by the shape of the plant and the structure of the leaves or needles. Considering individual leaves, deposition may be increased or reduced by different surface structures. (Kuttler , et al., 2008). Each species has a distinct ability to capture fine dust, and it depends by:

Macroscopic characteristics→ Structure of the plant

Microscopic characteristics →Structure of the leaf

2.5.1 Microscopic characteristics:

The leaf blade serves as the main plant structure that captures atmospheric PM; differences in leaf surface characteristics influence the ability of different plants to retain atmospheric PM. The microscopic traits of the leaves that affect the particulate capture and deposition capacity are:

- Roughness
- Waxy coatings
- Shape of leaves
- Leaf hairs

2.5.1.1 Roughness

Grooves are the main parts of a blade that adsorb $PM_{2.5}$. Deep grooves can intercept more particles and make the release of PM less likely. Shallow grooves result in only a low level of blade surface roughness and capture only a comparatively small number of particles. The roughness is greater, and the dust is more captured.

The ridges and grooves of epidermal cells and the density of micro-configurations, such as cell peaks, valleys, and recesses, determined the leaf surface roughness. The surface roughness of the leaves of broad-leaved tree species is greater than that of the leaves of needle-leaved tree species.

2.5.1.2 Waxy coatings

The epicuticular wax ultrastructure contributed significantly to the PM adsorption of the leaves. There is no real relationship between the amount of wax present on the foliar surface and the ability to capture the atmospheric particulate matter from the leaf itself. However, it is the type and chemical composition of the wax that influence its deposition. So, retention degree and particulate encapsulation vary depending on the cuticle's chemical composition (variability in the quantities of the individual wax constituents, responsible for the hydrophobia of the cuticle).

There may be different types of wax that cover the foliage. The three most common structures are thin films, platelets, and tubules. Several studies have been done on their different ability to contribute to particulate capture. These include the study carried out by (Wang, et al., 2015) , they have investigated the accumulation of particles on the leaf surfaces of three plant species with different epicuticular wax ultrastructure's, such as thin films, platelets, and tubules during leaf expansion in Bejing under extremely high particulate matter (PM) concentration. They discovered that the capability of these ultra-structures to capture PM decreased in the following order: thin films, platelets, and tubules. The hydrophobicity of wax particles on the leaf surface could lessen the ability of leaves to collect PM. (Mo, et al., 2015). Leaves with wax very crystals were less efficient than the species with wax films.

2.5.1.3 Shape of leaves

The shape of the deposition surface can directly influence the airflow pattern around the exterior and hence has a marked influence on PM deposition. Variable forms generate different drag forces due to wind, changing their effect on surrounding airflow patterns; the response of leaves to such forces can be swaying or fluttering. Hence, different levels of turbulence can result.

A study conducted by (U.Weerakkody, et al., 2018) analysed the impact of individual leaf traits on atmospheric particulate matter accumulation using natural and synthetic leaves. They discovered that there were significant differences in PM accumulation on leaves with different shapes. Smaller leaves showed a greater capacity to capture and retain particles, probably due to their more considerable edge effect. Palmately-lobed leaves showed high PM levels compared to elliptical or linear leaves as they may create more turbulence in the boundary air layer with their complex shape and "tip-like" areas. Palmately lobed leaves showed a more significant potential to capture and retain PM, probably due to their complex condition. Lobe leaves create more than one" leaf-tip-like" area creating a more complex morphology.

There is a pilot study that showed elevated PM accumulation at leaf tips. PM accumulation on elliptical and linear leaves was relatively poor. Even though linear leaves can be predicted to be good PM filters based on their large perimeter, they can also bend more readily with the wind flow (as these lengthy leaves are connected to a petiole with a narrow leaf base) without swaying with the wind currents, potentially resulting in lower levels of turbulence. However, despite having a linear shape, leaf needles are frequently cited as good PM filters, in addition to their epicuticular wax helping to provide a sticky surface to retain PM. This may also be attributed to their rigid/stiff nature compared to "grass-like" linear leaves.

2.5.1.4 Leaf hairs

Leaf hairs are important in increased PM accumulation by increasing surface area (for capture) and preventing captured PM re-suspension. Having such protruding structures can also create complex micro-topography on leaf surfaces, facilitating capture and retention of PM compared to smooth leaves. In addition, the hydrophobicity of some leaf hairs is known to have a positive impact on attracting metal-based charged particles (Mo, et al., 2015)

2.5.2 Macroscopic characteristics:

The plant species and planting configuration also affect deposition as the spatial structure of the vegetation. (Freer-Smith, et al., 2004) Analysing different species discovered that more complex stem structures and smaller leaves had greater relative deposition velocities, confirming the above on small leaves. Broadleaf species with rich leaf morphology, leaf groove, leaf hair and stomata, can capture more $PM_{2.5}$ per leaf area than coniferous. However, coniferous charged larger $PM_{2.5}$ per tree due to their large leaf area per tree. Conifers show the highest particle capture efficiency of tested species in all of the studies made on the velocity of deposition on trees. Among the conifers, pines captured significantly more PM2.5 than cypresses ones. A further disadvantage of deciduous trees is the lack of foliage outside the vegetation period, which, considered in absolute terms, reduces their filtration performance. However, technical problems such as the need to ensure adequate drive-through heights, reduced solar access for inhabitants in winter and poor resistance to pollutants restrict the possible applications of conifers in urban areas.

- Stem structure
- Difference between coniferous and broadleaf species

.

2.5.3 Plants particularly suitable for capture $PM_{2.5}$

According to the "Istituto di Biometereologia (Ibimet)" of the CNR of Bologna, VOC "Contained within the leaves, flowers or fruits to which they impart their pleasant scent, the VOC can quickly evaporate in the air and react quickly with the most common pollutants anthropogenic, if these are present at high concentration, contributing to the formation of gas toxic, such ozone and greenhouse gases. Conversely, in areas with low concentrations of such pollutants (such as rural ones), VOCs released by plants may instead lead to the removal of the ozone itself". About the selection of species with high particulate reduction capacity, it should be remembered that they must ensure low VOC emissions.

Name	**Family**	**Species**	**Dust Capture Potential**	**Characteristics**
Acero Campestre	Acero Campestre	*Sapindaceae*	High	furry leaves on both surfaces
Tiglio Selvatico	Tiliacee	*Tilia Cordata*	High	furry leaves on both surfaces
Olmo comune	Ulmaceae	*Ulmus minor*	High	leaves with rough surfaces and hairs on both surfaces
Mirabolano	Rosaceae	*Prunus cerasifera "pissardii"*	Good	leaves with a deeply wrinkled surface and simple hairs, even if thin on both sides

Table 2-1 Species characterized with a high capture efficiency of $PM_{2.5}$ with the description of their characteristics and explanation justify their high capacity.

Best species
Pseudotsuga menziesii
Cedrus libani
Picea abies
Cedrus atlantica
Pinus pinea
Pinus strobus
Quercus ilex
Pinus radiata
Pinus sp.
Pinus nigra
Pinus densiflora
Abies alba
Quercus suber
Cedrus deodara
Taxus baccata
Pinus taeda
Eucalyptus globulus
Fagus sylvatica
Thuja spp.

Table 2-2 Species characterized with a high capture efficiency of $PM_{2.5}$.

(Toscana, 2018), (Po, et al.) (Baraldi, 2011)

In addition, some trees are better able to survive in smoky and polluted conditions due to differences in the physiological mechanisms of varied species. All in all, the best choices for pollution-control plantings are coniferous and broadleaved species with rough leaf surfaces and high adaptability.

2.5.4 Effect of climatic Conditions on PM2.5 Concentration:

2.5.4.1 Wind speed:

Dry deposition velocity strongly depends on wind speed. The higher the wind speed, the higher is the friction velocity which accelerates the transport of particulate matter. This fact could be found in several works, indicating that a strong positive correlation exists between dry deposition velocity and wind speed. In most of the studies, dry deposition flux was well correlated with wind speed. (Mohan, 2015)

If the particulate matter has to be settled, atmospheric turbulence will play a significant role in it. Two meteorological parameters that influence atmospheric turbulence are friction velocity *(U*)* and surface roughness (Z_0). The relationship between these parameters for near-neutral atmospheric stability is

$$U = \frac{U^*}{k\ln(Z - d/Z_0)}\left[\frac{m}{s}\right] \tag{7}$$

U is the average wind speed, *Z* is the measured height above ground (usually 10 m), and k is the Von Karman's constant. Von Karman's constant is a dimensionless constant describing the logarithmic velocity profile of turbulent fluid flow, typically with a value of 0.4. Z_0 is the surface roughness coefficient; d is the datum displacement. Wind velocity affects airflow and the diffusion of airborne particulates. (Freer-Smith, et al., 2004) The particulate matter sedimentation rate under gale conditions [9ms^{-1}] was higher than under breeze conditions [3 ms^{-1}]. (Beckett, et al., 2000) found that when the wind velocity was less than eight ms^{-1}, the particulate matter sedimentation rate.

2.5.4.2 Temperature:

There have been several contradictory reports about the relationship between temperature and dry deposition velocity. In general, the higher the temperature, the stronger the atmospheric mixing, which decreases the atmosphere's stability. The decrease in the stability of the atmosphere would result in the turbulence effect of air. This turbulence would cause dispersion of particles when the particle concentration is high. Thus, dry deposition velocity is reduced. This would rise to the negative correlation between temperature and dry deposition velocity.

Furthermore, if temperature increases, the momentum of particles increases, paving the way for increase deposition velocity if particles fall in coarse particle range. In this case, a positive correlation would occur. For fine particles, this momentum effect is minor. With temperature, when particles show any or a combination of the behaviours as mentioned earlier, it can be determined where exists a positive or negative correlation between temperature and dry deposition velocity. (Mohan, 2015)

The variation of $PM_{2.5}$ concentration during an entire day can be explained as follows: the lower $PM_{2.5}$ concentration during the daytime is caused by the higher temperature, low relative humidity, and strong wind. (Yu, et al., 2015)

2.5.4.3 Humidity

An increase in relative humidity also influences dry deposition velocity. A relative increase would lead to an increase in particle size (hygroscopic growth). This growth can significantly increase the particle deposition rate. However, if the growth is not significant (dry season), relative humidity effects are considered minor (Mohan, 2015).

2.5.4.4 PM wash off.

The PM wash off process was related to rainwater accumulation and removal on the leaf surface. Firstly, there is an additional PM in rainwater and stemflow from top crown inputting on the leaf surface. Then the PM will be removed with drops and flows when the leaf water is over the storage capacity of the leaf. The process of accumulation and removal will exchange or recycle during a rain event. Differences in rainfall intensity might cause variations in PM wash-off processes. The species characteristics are the key factors that affect the rainwater interception efficiency and storage capacity. Relative to local features on the leaf surface, e.g., micro surface roughness, trichome density, stomatal density, the overall features (leaf area and leaf density (leaf number)) have a more substantial impact on the rainwater interception efficiency and storage capacity of plants.

There were considerable variations in the $PM_{2.5}$ numbers retained by trees at different time points under rainfall intensities. The rankings showed that rainfall had a more significant effect on the ability of broad-leaved trees to retain $PM_{2.5}$ compared with conifers, and trees with more complex structures and smaller leaves could better keep particles and had more stable $PM_{2.5}$ retention during rainfall events.

- ✓ broad-leaved trees with large leaves and simple crowns (bimodal curved)
- ✓ conifer species with small leaves and complex crowns under high rainfall intensity (unimodal curved)
- ✓ tree with extremely crowns under high rainfall intensity (continually rising curved)
- ✓ conditions under which extremely high-water interception efficiency but relatively low water storage capacity occur (U-shaped curved)

The cycles of $PM_{2.5}$ accumulation and removal on broad-leaved trees might be shorter than that of the conifers, meaning that they have a better $PM_{2.5}$ wash off-efficiency during rain, which is opposite to the $PM_{2.5}$ deposition efficiency. Higher rainfall intensity can reduce the cycle length and enhance the $PM_{2.5}$ wash off efficiency. (Xie, et al., 2019) In this study, four groups (I, II, III and IV) of wash-off processes (bimodal, unimodal, continually rising and U-shaped curves, respectively) were categorized. All procedures were well-fitted by quartic polynomial functions, although they followed patterns.

The processes of Group I was bimodal distributions, indicating PM2.5 retention changed easily and rapidly with an accumulation-removal cycle of 10-15 min. The processes of broad-leaved trees with large leaves and simple crowns always belonged to Group I. Broad-leaved trees have large leaves and simple structures, resulting in highly efficient interception of rainwater and, consequently, a short cycle of water accumulation and dripping.

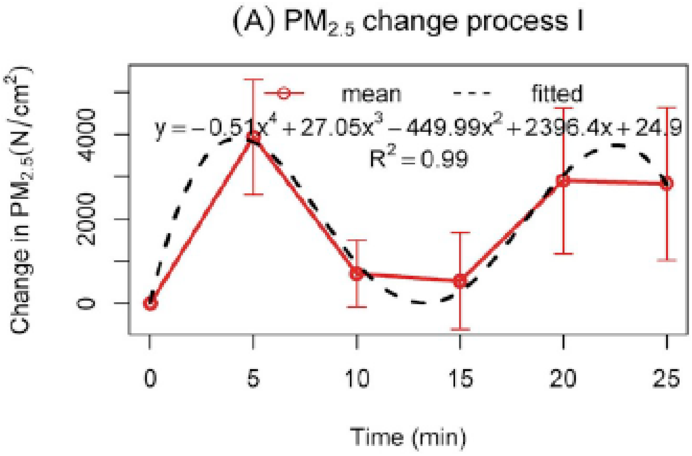

Figure 2-4Fitted models of the net change in PM2.5 over time for group A

The process of Group II was presented as a unimodal curve for 25 min; the $PM_{2.5}$ retained by leaves increased initially and then decreased, reaching a maximum value in 10-15 min. Group II processes occurred in trees with small leaves and complex crowns under high rainfall intensity. The processes of Group II had longer cycles than those of Group I. This may have occurred because of the lower rainfall interception efficiency of small leaves, and the extra water storage capacity associated with the complex crown and leaves could prolong cycles.

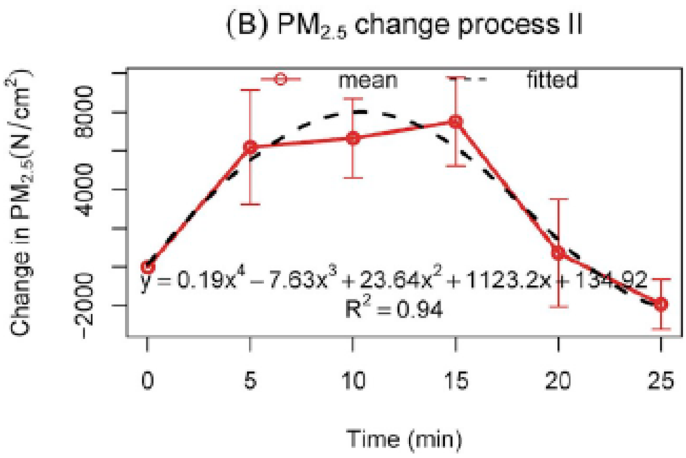

Figure 2-5 Fitted models of the net change in PM2.5 over time for the group B

The third type of wash off process showed a continuous increase with time and occurred mainly under high rainfall intensity and in trees with extremely complex crowns (e.g., Dragon Juniper). The underlying reason might be that for Group II, i.e., the highly complex crowns resulted in cycles even longer than the experimental duration of 25 min. The process of Group III indicated a positive accumulation with a continuous increase, indicating that $PM_{2.5}$ collection exceeded the amount that dripped from the leaves throughout the experiment. A large number of particles on the surface of complex branches might be inputted to the leaf surface with stemflow, which helps the $PM_{2.5}$ accumulation.

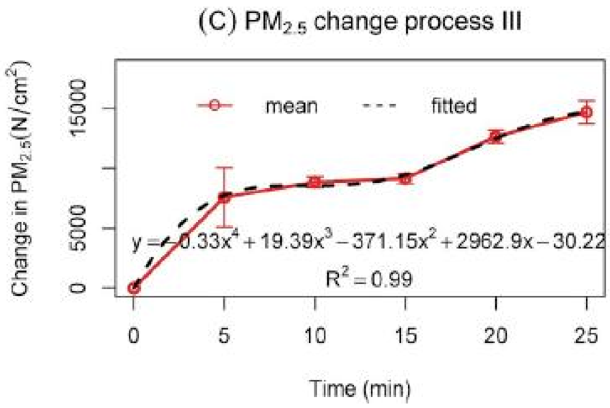

Figure 2-6 Fitted models of the net change in PM2.5 over time for the group C

The process of Group IV was an initial sharp decrease followed by an increase, i.e., a U-shape. This kind of process under the scenario where there was a short storage duration in the preliminary stage lengthened after the leaves became wet.

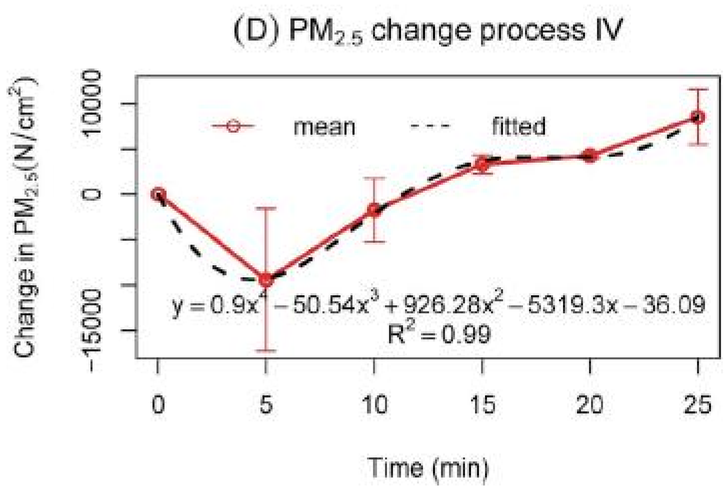

Figure 2-7 Fitted models of the net change in PM2.5 over time for group D

Broad-leaved trees probably have a better $PM_{2.5}$ wash off efficiency than conifers during rains.

They found smaller average values and larger max/min values of $PM_{2.5}$ retained on broad-leaved tree species in that study than on coniferous species. This indicates that the amount of retained particles on leaves of broadleaf species is lower. Its variance is higher, which means particles on leaves of broadleaf species can be washed out in rains more easily than on conifers. In general, there were more peaks in the $PM_{2.5}$ wash off processes of broad-leaved tree species compared with coniferous species in rainfall. The trees with a more complex structure and smaller leaves could better retain particles and had more stable PM2.5 wash off processes during rainfall events. The cycles of $PM_{2.5}$ accumulation and removal on broad-leaved trees could be shorter than those of conifers because the accumulation and removal processes of particulate matter on leaves are highly correlated with rainwater on leaves when raining. The larger leaves of the broad-leaved trees had higher water interception efficiency, while the more complex structure of conifers improved the water storage capacity.

Consequently, broad-leaved trees might have more rapid dripping than conifers and a more changeable $PM_{2.5}$ balance. The $PM_{2.5}$ wash off the efficiency of broad-leaved trees is higher than that of conifers, opposite the PM2.5 deposition efficiency. This means that both the adsorption capacity and wash off the ability of particulate matter need to be considered when screening trees for particulate matter purification. Higher rainfall intensity can shorten the cycle of PM2.5 accumulation and removal on leaves, resulting in the particulate matter on the leaf surface is effectively washed away. (Xie, et al., 2019)

2.5.5 Other parameters influencing the deposition of particles.

A variety of factors influences the deposition of particles on plant surfaces. The diameter and shape of the particles and meteorological such as humidity and turbulence is of decisive importance and have a considerable impact on deposition velocity and the filtration performance of plants. $PM_{2.5}$ removal is also affected by meteorological factors such as temperature, relative humidity, and wind speed, which all play an essential role. These have considerable influence on the amounts of $PM_{2.5}$ deposition and forest filtration performance.

2.5.5.1 Phoretic processes

Electrophoresis (electrostatic attraction), diffusiophoresis, and thermophoresis are processes that can influence the deposition of particles small enough to be affected by molecular collisions or to have high ion mobility. Phoretic processes are neglected in many dry deposition formulations. Electrophoresis or electrostatic attraction causes the movement of charged particles in the presence of an electric field. The direction of movement depends on the direction of the field and the sign of the charge on the particle. Attractive electrical forces have the potential to assist the transport of tiny particles through the quasi-laminar deposition layer and, thus, could increase the deposition velocity in situations with high local field strengths. However, Hicks et al. (1982) suggest that this effect is likely to be small in most natural circumstances.

Diffusiophoresis can change the rate of dry deposition of particles embedded in a surface gradient of a gas created by condensation or evaporation of the gas to/from the surface. There is a difference in the kinetic energies imparted by collisions, either up-gradient or down-gradient gas molecules. This process imparts momentum to the particles, which tends to move them down-gradient for denser-than-air gases and up-gradient for lighter-than-air gases. In addition, the introduction of new water vapour molecules at an evaporating surface displaces a specific volume of air. This effect, called Stefan flow, tends to reduce deposition fluxes from an evaporating surface. Thermophoresis results in a net directional particle transport in the presence of a thermal gradient. For a particle in a thermal gradient, the air molecules striking one side of the particle will be more energetic than those on the other side. This effect will tend to move small particles away from a heated surface and towards a cooled surface. (Droppo, 2006).

2.6 Fate of particle

Contaminants once deposited on vegetation migrate to other environmental matrices. Particles transferred from the atmosphere to foliar surface may reside on the leaf, twig, or bark surface for extended periods, be taken up through the leaf surface, or be removed from the plant via re-suspension to the atmosphere, washing by rainfall, or litter-fall with subsequent transfer to the soil and from there may have different destinies. The plant itself can reabsorb them through the roots or migrate to groundwater and surface water.

As mentioned above, PM is composed of several substances, and it is not easy to make a general speech regarding the migration of substances into other environmental compartments. We are therefore faced with the heterogeneity of chemical-physical properties that leads to entirely different behaviours of substances. It was therefore chosen to focus on a particular substance such as PAHs.

2.6.1 Example: Migration of PAHs from vegetation to other matrixes

Among the most dangerous compounds present within atmospheric PM are the PAHs (Polycyclic aromatic Hydrocarbons), a large class of toxic, mutagenic, and carcinogenic organic pollutants emitted to the atmosphere by incomplete combustion biomass or fossil fuel and from motor vehicle exhausts. The primary sources of PAHs are petrogenic and pyrogenic, resulting from anthropogenic activities, including direct inputs of petroleum and emissions from the combustion of oil, diesel, and biomass. Natural sources from volcanic activities and forest fires are marginal. As semi-volatile chemicals, the partition in the atmosphere between the gaseous and the particulate phase can be transported over long distances according to their specific physicochemical characteristics.

2.6.2 Uptake of atmospheric PAHs by vascular plants

Following atmospheric transport over variable distances and possible attendant transformations, PAHs are deposited on land and water surfaces through dry or wet deposition. Since PAHs are only poorly water-soluble, wet deposition-that is, solubilization in rainwater and fog is limited. Most PAHs are consequently deposited through the dry deposition of gases and particles. Particle-bound and gaseous PAHs undergo different fates because of their other properties and the range of environmental constraints for deposition.

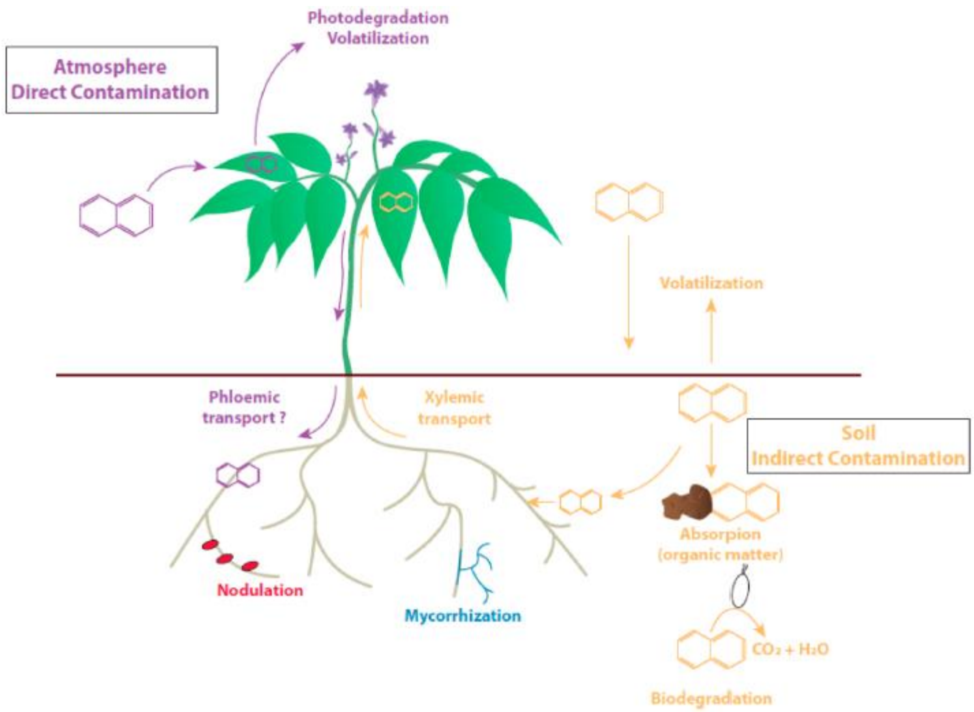

Figure 2-8 Paths of PAHs in soil, atmosphere, plants

In ecosystems and agrosystems, plants are exposed to atmospheric pollution by PAHs from the atmosphere but also the soil. Therefore, PAH concentrations recovered in vascular plants in situ represent integrative concentrations of two PAH exposure pathways, one pathway from the air to leaves (direct contamination, air-plant path) and the other from the perspective to roots, passing through the soil compartment (indirect contamination, air-soil plant pathway).

2.6.2.1 Indirect Contamination

Because of the high hydrophobicity of PAHs, they are generally assumed to be tightly bound to soil particles and weakly bioavailable even for the most water-soluble PAHs, which demonstrate high sorption to the organic matter in soil and low desorption capacity. However, plants also uptake PAHs from the ground. Many studies have focused on PAH transfer from soil to roots regardless of the previous soil contamination by atmospheric deposition in the literature.

2.6.2.2 Ecosystem response to indirect effects

In many cases, the more significant effects are indirect. These effects may be mediated by suspended PM (i.e., through effects on radiation and climate) and by particles that pass through vegetative canopies to reach the soil. Indirect plant responses of most significant interest are chiefly soil-mediated and depend primarily on the chemical composition of the individual elements deposited in PM. The individual components must be bio-available to affect. The soil environment (composed of mineral and organic matter, water, air, and a vast array of bacteria, fungi, algae, actinomycetes, protozoa, nematodes, and arthropods) is a dynamic site of poorly characterized biological interactions. The quantity of organisms in soils varies by locality. Bacteria and fungi are usually most abundant in the rhizosphere, the soil around plant roots that all mineral nutrients must pass through. Bacteria and fungi benefit from nutrients in the root exudates (chiefly sugars) in chemical and biological transformations, decomposing organic matter and making inorganic available for plant uptake and growth.

Fungi are directly essential to plant growth. Attracted to the roots by the exudates, they develop mycorrhizae, a mutualistic, symbiotic, that are integral to the uptake of the mineral nutrients. The impact on ecosystems of PM (particularly nitrates, sulphates, and metals) is determined by their effects on the growth of the bacteria involved in plant nutrient uptake. Indirect effects are usually chronic stresses. Responses of ecosystems to chronic stresses occur over time and are difficult to determine because the changes are subtle.

This is particularly true of responses to particles. Changes in the soil may not be observed until the accumulation of the pollutant has occurred for ten or more years, except in the severely polluted areas around industrialized point sources. In addition, the presence of other co-occurring contaminants makes it challenging to attribute the effects to PM alone. This is especially true when other pollutants present in the ambient air may produce additive or synergistic responses, even though PM concentrations may not change.

2.6.2.3 Direct Contamination

Transfer from Air to Leaves

Three main processes have been identified for PAH uptake by leaves from the atmosphere: equilibrium partitioning between the vegetation and the gas phase (i.e., diffusion), kinetically limited gaseous deposition, or wet and dry particle-bound deposition. Each of these processes depends on different atmospheric concentrations, environmental variables, and plant properties. The interception of particles depends on leaf orientation, surface area, and hairiness. Some plant types are much more efficient than others at intercepting and retaining particulate matter and associated PAHs.

(Desalme, et al., 2013)

2.6.3 Sources of PAHs in marine ecosystems

Pyrogenic PAHs, considered as chronic pollution, enter marine ecosystems mainly through fluvial run-off and atmospheric deposition (Figure 2-9), whose respective contributions depend on the distance from the point sources

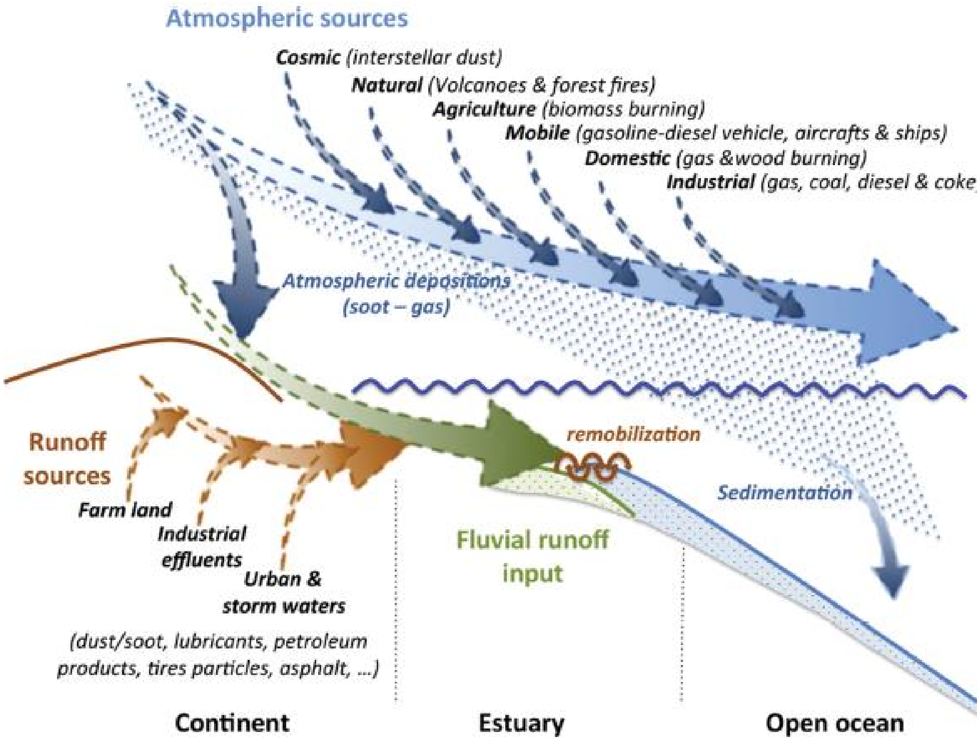

Figure 2-9 Different paths of PAHs in a marine environment

. In distant areas, the relative contribution of water run-off decreases, while that of atmospheric deposition increases. The latter is almost the principal PAH source in the surface water of open oceans. Oceanic water bodies are thus the final sink of atmospheric pollutants transferred to deep waters and finally trapped into sediments.

2.7 Urban Forest

To better understand the work of this thesis, it is necessary to introduce the concept of urban forest: Urban forestry is a specialized branch of forestry that has, as its objective, the cultivation and management of trees for their present and potential contribution to the physiological, sociological, and economic well-being of urban society" (Kielbaso,2008). An urban forest is roughly defined as a population of trees within the jurisdiction of a municipality. This includes street trees, trees on private property and parks, natural stands, and reserves within the management jurisdiction of municipalities. Few people know how many and what kind of trees are found in urban areas or how these trees affect a city's environment and the health and well-being of its inhabitants. Measuring the urban forest is one of the first steps toward understanding this resource and developing appropriate management plans. Understanding and quantifying the impact of urban trees is an essential prerequisite to managing city vegetation for optimal beneficial effects. (Nowak, et al., 1998)

3 MODELS

The modelling of deposition processes has been a topic of interest to the scientific community for at least forty years for various reasons: from the study of the deposition of radioactive particles following the Chernobyl accident (1986), the study of deposition mechanisms of air pollutants through the analyses of the fallout from acid rain (90's). This chapter presents a brief representation of commercial models such as ENVI-MET based on CFD modelling and Citygreen and an additional tool for GIS focusing on the i-Tree model used in this thesis. The same makers of "i-Tree" " (Nowak, et al., 2019)analysed the software's sensitivity to input data, sampling method, and leaf area estimation (LA). Through the study of (Szkop, 2020) it was possible to evaluate the sensitivity of the software to vary the concentration of pollutants inserted.

3.1 Types of models

To better manage urban forests and maximize tree benefits, several models have been developed and implemented. These models have been applied in case studies on individual locations and provide us with knowledge about urban tree services and benefits. In 2019 (Nowak, et al., 2019) analysed the case studies and articles published in the two previous decades about Urban Forest modelling. The analysis shows that the most used software is i-Tree, follows by CFD models (ENVI-met) and CITYgreen. A model is a simplified description of a real system with inputs, key components of the system and their relationships, and outputs constrained within specific spatial boundaries. A model can be developed based on either mechanistic approaches or empirical relationships, or a hybrid. The models considered must describe urban forest structure (e.g., size, species, composition, spatial configuration) and function (e.g., various ES) in highly complex systems.

3.1.1 I-Tree—(UFORE)

The origin of the i-Tree is the (UFORE) model and the Street Tree Resource Assessment Tool for Urban Forest Managers (STRATUM) model, which was released in the early 2000s. The first version of "i-Tree" was released in 2006. The programs were initially designed to aid in urban forest management but have since been expanded to meet the needs of multiple constituents, including rural forest managers, consultants, planners, homeowners, educators, and landscape professionals. The research and work of numerous people were instrumental in the evolution of I-Tree. The current version of the software is 6.0. Several tools are present within i-Tree, but those that interest this thesis work are i-Tree Eco and his light version "i-Tree Planting Calculator".

i-Tree Eco from the vegetation structure data present in the study area, obtained through sampling and weather data, returns the values of pollutants removed annually from the vegetation. Moreover, the value of ecosystem services quantifies the benefits also in monetary terms. In the specific case of $PM_{2.5,}$ the model quantifies the removal for dry deposition starting from the data on the deposition rate on the different species obtained from scientific studies and applying them to values of the vegetation surface area quantifies by the analysis of its structure.

3.1.2 CFD modelling of urban vegetation.

At the micro-scale, the CFD technique, even though computational expensive, is the preferred way of investigation and the most suitable for studies of various physical flow and dispersion processes in complex geometries such as cities. CFD offers some advantages compared to other methods since providing results of flow features at every point in space simultaneously and does not suffer from potentially incompatible similarities because simulations can be conducted at full scale.

Parametrization of aerodynamics effects

The representation of vegetation in the CFD modelling is crucial to capture its effects on wind flow in urban areas. The aerodynamic effects are investigated on the inclusion of trees with different approaches:

a) An implicit parametrization where three were included in the surface parametrization as a roughness length.
b) An explicit approach where trees were considered porous media and additional terms is added to the momentum and turbulence equations.

Results showed that only an explicit approach could be used to simulate wind flow in urban areas. In this sense, most CFD studies have considered vegetation as a porous medium, modelled by adding a momentum source (sink) term to the standard fluid flow equations.

Parameterizations of depositions and resuspension effects

In addition to the aerodynamic effects, vegetation removes pollutants from air through deposition on the leaves. Traditionally, this effect has been parameterized employing a downward flux as follows.

$$F_{depo} = V_d\left(z_{ref}\right)C\left(Z_{ref}\right)\ [kgm^{-2}s^{-1}] \tag{8}$$

C(z_{ref}) is the mean concentration of pollutants at z_{ref} [ms^{-1}]; this approach is used in mesoscale modelling. However, since the resolution at the microscale is much more refined and resolves the vegetation into several computational cells, urban vegetation has been modelled in CFD simulations as a volumetric sink term in the transport equation of pollutants. This term is proportional to LAD, V_d and pollutant concentration C(x, y, z) within each cell.

$$S_d = -LADV_dC(x,y,z)\ \ [kgm^{-3}s^{-1}] \tag{9}$$

The former equation works for homogenous vegetation surfaces. The leaves are aligned in a different orientation to the wind flows in the real world, which is not included in the equation. Thus, it can be seen as an average sink term of the trees on particulate over the whole tree crown area.

The particulate resuspension is usually neglected in CFD simulations. Recently, Hong et al. (2018) parametrized it in CFD simulations as a volumetric source term in the transport equation of pollutants (Bell and Treshow,2003)

$$S_r = LADV_rC_{sink}(x,y,z) \tag{10}$$

Additional Term [$kg\,m^{-3}s^{-1}$]	Deposition velocity V_d[$cm\,s^{-1}$]	References
$S_d = -LADV_dC(x, y, z)$	0.2–1 (for PM10)	Vos et al. (2013)
	0.5–5 (for PM10)	Vranckx et al. (2015)
	0.64 (for PM2.5)	Jeanjean et al. (2016) and Jeanjean et al. (2017)
	0.25–10 (Sensitivity analysis)	Santiago et al. (2017a)
	0.5–3 (for NOx)	Santiago et al. (2017b)
	4.58 (for PM2.5)	Hong et al. (2018)
$S_r = LADV_rC_{sink}(x, y, z)$	Resuspension velocity V_r [$cm\,s^{-1}$] Concentration deposited on plant C_{sink} [$kg\,m^{-3}$]	Hong et al. (2018)

Figure 3-1 Summary of additional terms added to the pollutant dispersion equation for modelling deposition and resuspension effects of vegetation and values deposition velocity used in CFD simulations.

Leaf Area Density LAD [$m^2\,m^{-3}$]	References
0.7 (Trees)	Vos et al. (2013)
2–5 (Hedges)	
1	Amorim et al. (2013)
1	Gromke and Blocken (2015a)
0.55–2	Gromke et al. (2015)
1.6–4	Vranckx et al. (2015)
1.6	Jeanjean et al. (2015), (2016)
0.1–0.5	Santiago et al. (2017a,b)
1–1.6	Jeanjean et al. (2017)
0.5–2	Moradpour et al. (2017)
2.3	Hong et al. (2018)

Figure 3-2 Summary of leaf area density (LAD) values used in the CFD simulations.

Among the software that exploits the CFD modelling method, there is ENVI-met.

3.1.2.1 ENVI-MET

ENVI-met is a prognostic three-dimensional microclimate model designed to simulate the surface-plant-air interactions in urban environments with a typical resolution down to 0.5m in space and 1-5s in time. Steady-state CFD simulations for neutral conditions were performed for different wind directions and speeds according to the meteorological input for each selected time slot of the short-term measurement campaign. In the research community, ENVI-met is widely used in human biometeorology and thermal comfort studies. However, the model also features a pollution dispersion module to simulate numerous points, line and area sources of substances, e.g. NO, NO_2, O_3 and PM, becoming more and more popular. It includes particle sedimentation depending on size and mass, and deposition at surfaces. The model is extended with a module for the dispersion of gases (NO, NO_2, O_3, SO_2) and particles (mass-based PM_{10}, $PM_{2.5}$, elemental carbon.

The model has a dry deposition scheme of resistances. Deposition can occur on different surfaces-building walls and roofs, vegetation, and soils. Envi- met has features that are not common for other CFD dispersion codes, i.e. a detailed microclimate module and a vegetation module. The initial parameters required as an input in ENVI-met are meteorological data (wind speed and direction at 10m height, relative humidity, and temperature), emissions and domain characteristics.

A simple upstream advection approach is used to calculate the pollutant dispersion. ENVI-met is based on a three-dimensional computational fluid dynamics (CFD) model. The CFD model solves the Reynolds-averaged non-hydrostatic Navier-Stokes's equations for each spatial and grid cell and time step. Turbulence is calculated using the 1.5th order closure k-ε model. Two predictive equations are used to solve the variables k and ε, determining the kinetic energy in the turbulence and the turbulent dissipation, respectively. In consequence, these two equations represent the turbulent properties of the flow. (Schneider, et al., 2016)

Pollutant dispersion

The dispersion of particles is modelled with the three-dimensional (3D) computational fluid dynamics (CFD) model ENVI-met is RANS /Reynolds Averaged Navier-Stokes) equations based, non-hydrostatic micro-scale obstacle-resolving model with advanced parametrizations for the simulation of surface-plant-air interactions. ENVI-met uses the Eulerian approach to study the dispersion of pollutants, allowing simulation of pollutant dispersion, including particles, passive gases, and reactive gases. The dispersion of pollutants is calculated using the standard advection-diffusion governing equation. By adding source and sink terms in the equation, local processes that influence the change in concentration of local pollutant source or the deposition of particles can be parametrized. As a result of gravitational forces, particle deposits on different surfaces, including building walls, roofs, vegetation, and soil, also known as particle sediment, are considered in this model. The pollution source in ENVI-met is defined in the model domain and can be line-, point- or area sources with hourly emission rates.

Vegetation

Vegetation is treated as a one-dimension column. The physical characteristics (shape and height) of vegetation are parametrized using the leaf area density [LAD, m^2/m^3], which is defined as the total leaf area divided by the total volume of vegetation. The height of the plant z_p is divided into ten layers (whose height is expressed as $z_{pl}=z_p/10$), and a leaf area density value is assigned to each layer.

LAD is an essential parameter in the calculation of the mass particles deposited. The filtering capacity of vegetation is defined as a sink term in the dispersion equation. The aerodynamic resistance and sublayer resistance (quasi-laminar resistance) are considered in calculating particle deposition velocity. (Buccolieri, et al., 2018)

3.1.2.2 Future requirements in experiments and CFD modelling

The developed parametrizations of trees (and urban vegetation in general) are appropriate for considering deposition and the aerodynamic effects on air quality in urban areas. Validation studies, mostly performed using wind tunnel experiments, have shown a good performance of CFD modelling provided that the appropriate turbulence closures and tuning of some parameters are employed. The analysis of the literature has also pointed out some shortages and future perspectives:

- Resuspension and thermal effects of vegetation have been considered in few studies. There is the need for more works to gain confidence in the accuracy of their parameterizations of aerodynamic and deposition effects.
- Emissions of VOCs from vegetation and chemical reactions may be sink or source of NOx and O_3 and thus strongly affect the pollutant concentrations in urban areas. Such effects are usually neglected in CFD modelling.
- Wind tunnel studies employed for validation purposes refer to idealized scenarios under specific meteorological and conditions and for limited combinations of different types of vegetation (e.g. trees, hedges) and LAD. There is the need for systematic and comprehensive, including resuspension and thermal effects of different types of trees and vegetation in general. This would allow evaluating the dominant influence for the different scenarios better and provide a valuable suggestion for planning purposes. (Buccolieri, et al., 2018)

3.1.3 CITYgreen

A CITYgreen model is an effective tool developed by American Forest for estimating the ecological benefits of green space and translating the abstract benefits into concrete economic values. Combined with high-resolution satellite images from which detailed ground data can be extracted, CITYgreen can assess the benefits of green spaces over large areas with reliable results. As a result, CITYgreen has been widely used in more than 200 cities in the United States to guide public decisions about environmental management, land use and afforestation. As an extension of ArcView GIS, CITYgreen can be used to calculate green space benefits in terms of carbon fixation, pollution remediation, energy-saving, and storm runoff reduction based on a created "green data layer" of study areas and the spatial analysis function of GIS. There are two sections embedded in the CITYgreen The database sections contain spatial data and attribute data. The benefit assessment section uses spatial and attributes data to analyse and calculate each ecological benefit of the green space. Furthermore, a process of tree growth modelling can also be accommodated by CITYgreen to predict the future benefits of green spaces. (Peng, et al., 2008)

3.1.4 Choice of Model

CFD models, such as ENVI-met, allow precise analysis because they consider the phenomenon of dispersion but have a large limit. Their applications require extensive mathematical, scientific knowledge and do not allow investigations to be carried out in large areas such as urban areas. It is, therefore, a less usable model than the other two. CITYgreen is a model that has been used mainly in the United States and is not widely spread internationally as is i-Tree. The choice of the model to be used in this thesis fell on i-Tree, as reported by the study carried out by (Nowak, et al., 2019) is widely the most popular model such dissemination is because it is free software and that through the guidance provided by the creators of the model make it easy to use. The deposition processes considered by the following models are those already mentioned in Chapter 1: Brownian motions, interception, and impaction.

3.2 UFORE model

3.2.1 History

Scientists developed the UFORE (Urban Forest Effects Model) from the United States Department of Agriculture (USDA) Forest Service in the 1990s in conjunction with the State University of New York (SUNY). It was developed as a means by which urban forest managers could accurately quantify forest structure and functions (Nowak e Crane,1998). The system uses field measurements, tree cover, meteorological and air pollution data to produce forest structure metrics, volatile organic compound emissions, carbon storage sequestration and hourly air pollution removals. The UFORE model uses comprehensive results from a series of research projects conducted by its developers to produce output parameters for functional urban forest managers (Nowak et al., Nowak e Crane,2002, Nowak et al., 2006). (Langley, 2012).

3.2.2 UFORE Methods

The UFORE model uses standard field, air pollution, and meteorological data to quantify urban forest structure and numerous forest-related effects in various U.S. cities (Nowak and Crane 2000). Currently, there are five model components:

UFORE-A: Anatomy of the Urban Forest—quantifies urban forest structure (e.g., species composition, tree density, tree health, leaf area, leaf and tree biomass) based on field data.

UFORE-B: Biogenic Volatile Organic Compound (VOC) Emissions—quantifies 1) hourly urban forest VOC emissions (isoprene, monoterpenes, and other VOC emissions that contribute O_3 formation) based on field and meteorological data, and 2) O_3 and CO formation based on VOC emissions.

UFORE-C: Carbon Storage and Sequestration—calculates total stored C, gross, and net C sequestered annually by the urban forest-based on field data.

UFORE-D: Dry deposition of Air Pollution—quantifies the hourly amount of pollution removed by the urban forest and associated per cent improvement in air quality throughout a year. Pollution removal is calculated for O_3, SO_2, CO, PM_{10} and $PM_{2.5}$ based on field, pollution concentration, and meteorological data.

UFORE-E: Energy Conservation-estimates effects of trees on building energy use and consequent carbon emissions from power plants. (USDA).

3.3 I-Tree--(UFORE)

3.3.1 Tools

3.3.2 Tools available only in the United States

i-Tree tools aid in forest management decisions, education, and advocacy by working at various scales: from the individual tree to the property, neighbourhood, city, and landscape levels. The entire suite was developed to analyse urban greenery based on the climatic, environmental, and social conditions of the United States so that all i-Tree programs can be used in the USA. Moreover, in the States, the full potential of each component can be exploited, reaching the maximum precision of the results. This section describes the programs that can be used exclusively in the USA (with some exceptions available in Canada):

- i-Tree Streets
- i-Tree Landscape
- i-Tree Design
- i-Tree Species
- i-Tree My Tree
- i-Tree Vue
- i-Tree Harvest Carbon Calculator

3.3.2.1.1 Tools for Italy

Here are the suite programs used in countries outside the United States, particularly in Italy. Through these tools, it is possible to determine the ecosystem services of urban greenery, assessing the environmental benefits, such as removing pollutants and oxygen production, and the extent of the surface outflows during weather events. To obtain results from the analysis of the programs, it is necessary to first characterize the locality in question by specifying a city with climate conditions as similar as possible, then enter the data measured in the field to describe the area being studied. Below is a brief description of the programs available in Italy. . (USDA, 2020) (Fumero, 2018)

- **I-Tree Eco:** provides a broad picture of the urban forest or trees in your study area. It is designed to use field data from complete inventories of trees or randomly located plots throughout a community along with local hourly air pollution and meteorological data to quantify urban forest structure, environmental effects, and value to communities.
- **I-Tree Hydro:** is the first vegetation-specific urban hydrology model. It is designed to model changes in urban tree cover and impervious surfaces on hourly stream flows and water quality at the watershed level.
- **I-Tree Database:** is an online system designed for international users outside of the United States, Canada, Mexico, Australia, South Korea, Colombia, and most countries in Europe to submit adequately formatted global pollution and weather data, location information, new species information, and other requirements needed for the i-Tree Eco model to process in a new, previously unsupported study area. The submitted data will be vetted by the U.S. Forest Service and integrated into the Eco model as a new international location available for automated processing in future Eco updates. It has also presented a rich collection of plant species in the Database to which users can assess and add new elements. This system opens the prospects of worldwide use, although the timing of the approval phase can be quite prolonged.
- **i-Tree Canopy** offers a quick and easy way to produce a statistically valid estimate of land cover types (e.g., tree cover) using aerial images available in Google Maps. Urban forest managers can use the data to estimate tree canopy cover, set canopy goals, and track success, and estimate inputs for use in i-Tree Hydro and elsewhere land cover data are needed. The canopy also estimates tree benefits based on the amount of tree cover in your study area.

3.3.2.2 Methods, advantages, and limitations

The premise behind I-Tree is shown in Figure 3-3. The structure is the basic information on the physical forest resource (e.g., number of trees, species composition, tree sizes and locations, leaf area, etc.). The attributes are directly measured by users or estimated (e.g., leaf area) by I-Tree based on direct structure measures. From the structure data, along with environmental data (e.g., weather data), various tree functions (e.g., gas exchange, tree growth) are estimated. These functions are then converted to multiple services (e.g., pollution removal) based on other data (e.g., local atmospheric conditions, human population data). Finally, the benefits are converted to values based on various economic procedures. i-Tree is designed to aid managers by providing essential data on forest structure, services, and values. The i-Tree team is also working on delivering management guidance related to the best species and locations to sustain or enhance forest health, services, and values through time. There are four main steps needed to quantify the benefits and discounts from forests (Nowak 2018)Quantify the forest structural attributes that provide the service for the area of interest (e.g., number of trees, tree cover). These structural data are essential as they quantify the resource attributes that provide the services.

1) Quantify how the structure functions and influences the ecosystem service (e.g., tree density, tree sizes, and forest species composition are significant drivers for estimating carbon storage).
2) Quantify the benefit of the selected ecosystem service. In many cases, it is not the service itself that is important, instead the impact that the service has on human health or other environmental attributes that value society.
3) Quantify the economic value of the impact provided by the ecosystem service.

Forest structure must be accurately assessed. Inaccurate measurement of structure will lead to approximate estimates of subsequent services and values. Similarly, the validity of the models and data used to estimate benefits and values will impact the accuracy of these estimates. As with any assessment and modelling framework, there are trade-offs among selected methods regarding efficiency, cost, practicality, and accuracy. All current estimates and means of estimation can be improved to varying degrees.

Figure 3-3 Diagram showing basic i-Tree process.

(Nowak, 2020)

3.3.2.3 i-Tree Eco

Eco is unusable for a new location without the contribution of the Database data, as the latter may prove superfluous without the application achieved by the first. On the contrary, data are already available. They refer to a city that falls in one of the countries mentioned above, or because previously inserted by another user, it can directly create a simulation with Eco.

3.3.2.3.1 Assessing Forest Structure in I-Tree ECO

Good forest structure data are critical to I-Tree. These data can vary from information about an individual tree to consolidated information about the entire forest. Forest population data can be derived from an inventory of the population, where all trees are measured, or from a population sample. Some subsets of the population are randomly selected, and the population total is estimated from this sample. Before taking the model, land managers can decide whether the data will be collected with a certain number of plots in each land use type (e.g., pre -stratified) or collected randomly from plots and later categorized by land-use type (e.g., post-stratified). Pre-stratification can reduce the statistical variance and allow users to put more plots in desired strata (e.g., putting more plots within forested urban areas). However, estimates of change through long-term monitoring of the plots are complicated as the strata can change through time. Post-stratification, the randomly located plots can be reclassified into most strata classification after data collection (e.g., land use, management zones). This post-stratification may not be the most efficient in reducing variance but allows for more accessible change assessments.

There is no estimate of variance or sampling error in the population total as the entire population is inventoried with an inventory of all trees. With a sampling of a subset of trees, the standard error of the population estimate is calculated. Users can select which assessment method is most appropriate for their population (i.e., inventory, pre-stratified sample, or random sample with post-stratification). Inventories likely work best for small populations of trees or populations where intensive management is conducted on each tree (e.g., street tree populations). As previously mentioned, the UFORE model that deals with evaluating the urban forest structure is module A.

On each plot, the following general plot data were estimated/recorded:

- Per cent tree cover
- Actual land use on the plot
- Per cent of plot within land use
- Ground cover: per cent of ground covered by following cover types: buildings, cement, tar-blacktop/asphalt, other impervious, soil, previous rock, duff/mulch, herbaceous (exclusive of grass and shrubs), maintained grass, wild/unmaintained grass, and water,
- Per cent shrub cover

For each shrub mass, the following information was recorded: genus, height, per cent of shrub mass volume devoid of leaves, and cent of shrub area in the plot occupied by the shrub mass. For each tree with the centre of its stem in the plot, minimum diameter at breast height (d.b.h.) of 2.54 cm, the following information was measured/recorded:

- Species
- Number of stems
- d.b.h of each stem (or if greater than six stems, diameter recorded below fork and height of measure recorded)
- Tree height
- Height to base of live crown
- Crown width (average of two perpendicular measurements).
- Per cent of branch dieback in a crown (used to rate tree crown condition):
    - E (<1)
    - G (1-10)
    - F (11-25)
    - P (26-50)
    - C (51-75)
    - D (76-99)
    - K (100—no leaves)
- Per cent of canopy volume devoid of leaves (0-100%)
- Per cent of the land area beneath the entire tree canopy’s drip line is impervious.
- Per cent of the land area beneath canopy drip line that is occupied by shrubs.
- Crown Light Exposure: Number of sides of the tree receiving the sunlight from above.
- Distance to a residential building (if with 60 feet of tree)
- Direction to a building.
- Street tree: Y if a street tree, N if not.

TREE MEASUREMENTS

In each case study, one-tenth circular acre plots were established across the entire city area using simple random sampling, and tree species, diameter at breast height (DBH), tree height crown height and width, tree condition, crown light exposure (CLE), and per cent leaf dieback were measured. DBH is estimated at 1.37 m above the ground using a DBH tape.

Tree height is measured as the height from the ground to the top of the tree. Crown height is equal to the height difference between the live top of the tree and the crown base, while crown width is the average of the widths of the crown in the north-south and east-west directions. The crown diameters were measure by clinometer or laser device. Tree condition (crown dieback) is estimated based on the per cent of the crown composed of dead branches with 5 per cent classes. CLE is the number of sides of the tree receiving the sunlight from above (ranging from 0 to 5), which is employed to estimate competition and growth rates. i-Tree defines a tree as any woody plant with a diameter at breast height (d.b.h.; defined as the measurement at 1.37 m [4.5 ft]) greater than or equal to 2.54 cm (1 inch). A shrub is defined as any woody plant with a d.b.h. Less than 2.54 cm. However, users can set their classification of the tree versus shrub (e.g., based on species).

3.3.2.3.2 Calculation of LEAF AREA and LEAF AREA INDEX(LAI)

The cumulative leaf area in an urban forest canopy is an essential variable influencing air pollution removal. It is one of the main sources of uncertainty about the final result, so it is necessary to calculate this value precisely. Leaf area is defined simply as the surface area (one-sided) of leaves on a tree. Leaf area measurements are “scaled up” to cover an entire urban forest. The cumulative amount of leaf area per unit of the projected ground surface area is known as the leaf area index (LAI= leaf area [m^2] / ground area[(m^2]). The i-Tree Eco model uses tree-specific CLE values that are grouped into three states to calculate LA: The open-grown (CLE=4-5), park (CLE=2-3), and closed forest (CLE=0-1) conditions.

Under the open-grown condition, LA is calculated either from DBH only (measured at 1.37 m above ground) or from crown length(H) and crown width(D) if available:

- CLE=4-5 (open-grown trees)

$$\ln(LA) = b_0 + b_1 DBH + b_2 S \quad (11)$$

$$\ln(LA) = b_0 + b_1 H + b_2 D + b_3 S + b_4 C \quad (12)$$

In these calculations, S is a species-specific shading factor, which is defined as the percentage of light intensity intercepted by foliated tree crowns, and C is the outer surface area of three crowns calculated from H and D as $C = \pi D(H + D)/2$. S varies with species for deciduous trees, and if it is not defined for individual species, the averages for the genus or general hardwoods are used. The model applies a shading factor of 0.91 for all species for conifer trees, except for pines (0.83).

For the closed forest condition, LA is calculated using the following equation based on the Beer-Lambert law:

- CLE=0-1 (forest stand condition)

$$LA = (\ln(1 - S)/-k) \times \pi \times (D/2)^2 \qquad (13)$$

k is a light extinction coefficient differentiated between conifers (0.52) and hardwoods (0.65).

- CLE =2-3(park condition), LA is calculated as the average value determined by the open-grown (CLE=4-5) and closed canopy equations (CLE=0-1).

Estimates of LA and leaf biomass are adjusted downward based on crown leaf dieback (tree condition). Trees are assigned to one of seven condition classes: excellent (less than 1% die-back); good (1% to 10% dieback); fair (11% to 25% dieback); poor (26% to 59% dieback); critical (51% to 75% dieback); dying (76% to 99 % dieback); and dead (100% dieback). Condition ratings range between 1, indicating no dieback and 0, indicating 100% dieback (dead tree). Each class between excellent and dead is given a rating between 1 and 0 based on the mid-value of the class (e.g., fair=11% to 25% dieback is given a rating of 0.82 or 82% healthy crown). Tree leaf area is multiplied by the tree condition factor to produce the final LA estimate.

3.3.2.4 i-Tree Database

i-Tree Database is an online application for users who want to analyse outside of those countries for which data have already been entered in i-Tree Eco, namely the USA, Canada, Mexico, UK and Australia. It, therefore, has an auxiliary function to Eco, making it accessible to so-called international users. This service represents the real fulcrum of removing the geographical boundaries of the suite and, in particular, of Eco. It has allowed the latter to appear as the most useful software, in this sense, of the I-Tree package. The Database is divided into two sections: the species and the localities. The first consists of a rich collection of plant species (more than 6500 trees and shrubs), with attached the information necessary for the functioning of the program, such as botanical classification (scientific name and common name, genus, family, class), foliar density, growth rate, leaf characteristics (shape, size, fall period). In case of lack of species, it can be incorporated into the Database by inserting the data through the online application. Following is a phase of formatting and validation of data by the U.S. Forest Service. At the end of this step, the new species is added to the collection of those already present and made automatically available to all users for any project. (Nowak, et al., 2008)

The second section includes all the locations already included in the Database that contains the countries mentioned above and the new cities for which users have entered the data. The latter is recorded in the New City List. A list made public on the website of I-Tree, from which users can take note of the locations now available to use Eco.

Figure 3-4 USA divided into different climate zones utilizes for the USA country and the analogy with the overseas countries

The procedure to add a new location is to specify the latitude and longitude required to indicate a climate region in the USA inside which the user identifies a city with climatic characteristics as similar as possible to the new location. There is a systematic procedure based on a parameter, the mean square error (RMSE), calculable in the following way to distinguish this city.

$$RMSE = \sqrt{a * (HDD_{SC} - HDD_{RC})^2 + b * (CDD_{SC} - CDD_{RC})^2 + c * (AP_{SC} - AP_{RC})^2 + d * TM_{RC}^2} \tag{14}$$

where:

- HDD_{SC} and HDD_{RC} are the Heating Degree Days of the city subject to analysis and the US city of reference. It is a summary of fluctuations in air temperatures as a function of the heating buildings.
- CDD_{SC} and CDD_{RC} are the Cooling Degree Days respectively of the city subject to analysis and the Us city of Reference. Also, in this case, it indicates the external temperatures based on the cooling of a building.
- AP are the heights of rain annual
- TM (Tree Match) is a factor that results from the comparison of the 22 main plant species of the two locations and will be all the closer to zero the more ecosystems resemble each other.
- a,b,c,d are weighting factors to determine the importance attached to the four different parameters by which they are multiplied and influenced by the accuracy with which they are derived.

The location leading to the minimum value of RMSE is the best match.

This process determines the energy characteristics of the area in question and the influence of the trees on them, assuming that they are the same as the reference city. It is a method that can be costly and complex but has precise results. However, the Database simply requires to enter the reference climate region but does not specify how it should be recognized so that the user can roughly choose it. However, it should be noted that this information is transmitted to Eco, and the approximations of the analyses carried out by the latter are as relevant as the characteristics of the foreign location differ from those of the American city.

The location described above is associated with rainfall heights and concentrations in the air of fine dust ($PM_{2.5}$), carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2). Each of these data shall be measured hourly over at least one calendar year, from 1 January to 31 December. The documents to be uploaded online must be spreadsheets in which all the necessary information is described, following precise formatting. If no precipitation data are available, Eco will not assess water outflows in the presence of vegetation. Similarly, the model will perform an estimate of the benefits brought by urban green relating exclusively to the pollutants included in the Database: in the most extreme case, for none of them. In this case, there is also the phase of control and approval of the U.S. Forest Service's data. The new location will be incorporated into Eco thanks to a periodic update of the software. By running the update, all users will be able to take advantage of the new data, so it is recommended to frequently check the availability of a new version of the program.

The system described above has allowed access to I-Tree to international users, ensuring the reliability of the data and, consequently, the results of Eco. However, the method still has a long-time frame, reaching several months if you consider the data collection and the validation period. What is more, if the data has inaccuracies in formatting or content, the time dilates further not only for the user who sent them but also for those conducting the same procedure. (Fumero, 2018)

3.3.2.5 i-Tree as Bottom-up approach

There are two basic ways of assessing the structure or composition of the urban forest:

- **Bottom-up approach.** Field-based assessments to measure the physical structure of the forest (e.g. species composition, number of trees)- typically used for strategic resource management or advocacy by connecting forest structure, functions and values with management costs, risks, and needs.
- **Top-down approach.** Assessments of canopy cover using aerial or satellite images-used to determine amount and distribution of tree cover, potential planting space and other cover types.

I-Tree follow a bottom-up approach. The bottom-up approach: field-based assessments

Advantages:

- Provides reasonable estimates of basic forest information needed for management (e.g., number of trees and locations, species composition, tree sizes, tree health, risks).
- Provides estimates of numerous ecosystem services and their values.
- It can be used for monitoring changes in forest composition and values.

Disadvantages:

- Must collect accurate field data using technical metrics.
- Cost of data collection

Cost:

Varies with the size and scope of the project. Volunteers, in-house crews and hired consultants have all been employed for collecting data. Hiring a consultant to carry out a typical i-Tree Eco sample of 200 plots could cost $40 000 at a contracted rate of 200$ per plot. Costs would decrease with volunteers or student labour (e.g., 20 000 $ with students, even less with volunteers. Sampling intensity is determined by the user based on the accuracy desired and the resource available.

Accuracy:

Varies on sample size and accuracy of data collection, 200 one-tenth acre plots typically produce a relative standard error of less than 15 per cent for the population estimate.

(USDA)

3.3.3 i-Tree Eco Dry Deposition Model Descriptions

Employing field-surveyed urban forest information, location-specific data, weather data, and air pollutant measurements, i-Tree Eco assesses the structure of community trees and quantifies the environmental services that trees provide. I-tree Eco was developed based on the Urban Forest Effects (UFORE) model. With its dry deposition component (UFORE-D) integrated into i-Tree Eco, dry deposition of air pollution (i.e., pollution removal during nonprecipitating periods) to trees and shrubs and associated per cent improvement in air quality can be estimated with i-Tree Eco. The dry deposition of criteria air pollutant's (CAPs); carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulphur dioxide (SO_2), and particulate matter less than 10 microns (PM_{10}) can be assessed with version 4. In addition, particulate matter less than 2.5 microns ($PM_{2.5}$) can be evaluated with version 5. Pollutant flux is calculated as a product of the deposition velocity and the air pollutant concentration.

$$F = V_d \times C \qquad (15)$$

3.3.3.1 Deposition velocity calculation for PM_{10}

Deposition velocity for PM_{10} is calculated based on average, minimum and maximum values reported by Lovett (1994).

In-Leaf Periods:

Deposition velocity for PM_{10} is calculated based on average, minimum, and maximum values reported by Lovett (1994)

$$V_d = V_{d,PM,Avg} \times \frac{BAI + LAI}{BAI + LAI_{PM10}} \left[\frac{m}{s}\right] \tag{14}$$

$$V_{d,Min} = V_{d,PM,Min} \times \frac{BAI + LAI}{BAI + LAI_{PM10}} \left[\frac{m}{s}\right] \tag{15}$$

$$V_{d,Max} = V_{d,PM,Max} \times \frac{BAI + LAI}{BAI + LAI_{PM10}} \left[\frac{m}{s}\right] \tag{16}$$

where:

$V_{d,PM,Avg}$ = Average deposition velocity for PM_{10} (=0.64 ms^{-1}) (Lovett 1994)

$V_{d,PM,Min}$= Minimum deposition velocity for PM_{10} (=0.25 ms^{-1}) (Lovett 1994)

$V_{d,PM,Max}$=Maximum deposition velocity for PM_{10} (=1.00 ms^{-1}) (Lovett 1994)

LAI_{PM10} = Leaf area index for particle deposition (=6)

BAI = Bark area index

LAI=Leaf area index

Out-Leaf Periods:

$$V_d = V_{d,PM,Avg} \times \frac{BAI + LAI_{evergreen}}{BAI + LAI_{PM10}} \left[\frac{m}{s}\right] \tag{17}$$

$$V_{d,Min} = V_{d,PM,Min} \times \frac{BAI + LAI_{evergreen}}{BAI + LAI_{PM10}} \left[\frac{m}{s}\right] \tag{18}$$

$$V_{d,Max} = V_{d,PM,Max} \times \frac{BAI + LAI_{evergreen}}{BAI + LAI_{PM10}} \left[\frac{m}{s}\right] \tag{19}$$

where:

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

The output hourly pollutant flux (grams per m^2 of tree canopy per hour) is calculated as the product of the deposition velocity (meters per second) and pollutant concentration (grams per m^3).

3.3.3.2 Deposition velocity calculation for $PM_{2.5}$

Deposition velocity calculation for $PM_{2.5}$ to trees was estimated from literature and varied with wind speed (Beckett et al. 2000, Freer-Smith et al. 2004, Pullman 2009). These papers measured deposition velocities to tree leaves from 17 tree species under wind speeds of 1,3,6,8,9 and 10 ms^{-1}. For each wind speed, the median deposition velocities from the measured deposition velocities were used to estimate $V_{d,}$ $PM_{2.5}$ for that wind speed per unite leaf area (Table1).

$$V_d = V_{d,PM2.5} \times LAI \qquad (20)$$

The standard error of the estimates among the species was used to estimate a potential range of value of deposition velocities. The median deposition velocity per wind speed plus 1.96 times the standard error was used to estimate a maximum deposition for the wind speed ($V_{d,\ PM2.5,\ Max}$). Using standard errors to estimate the lower range of deposition produced negative deposition velocities, the minimum average V_d from any species was used to represent the minimum V_d for the wind speed ($V_{d,\ PM2.5,\ Min}$). To estimate the V_d for the wind speeds between and 10 ms^{-1} that did not have a measured V_d, values were interpolated between the closest measured values. For wind speeds above 10 ms^{-1} was used; for a wind speed of 0 ms^{-1}, the V_d was assumed to be 0 cms^{-1} (Table2).

$$V_{d,min} = V_{d,PM2.5,min} \times LAI \qquad (21)$$

$$V_{d,max} = V_{d,PM2.5,max} \times LAI \qquad (22)$$

Resuspension of $PM_{2.5}$ from trees was estimated from Pullman (2009) and varied with wind speed. This paper measured per cent resuspension. The measured per cent resuspension of $PM_{2.5}$ from tree leaves of three species is under wind speeds of 6.5,10 and 13 ms^{-1}. The average per cent resuspension for three species and wind speed was calculated (Table 2). As the per cent resuspension for the wind speed of 6.5 m s^{-1} was 9.5%, a value of 9% was assumed for a wind speed of 6 ms^{-1} and 10% for 7 ms^{-1}.

The per cent resuspension for a wind speed of 0 ms^{-1} was assumed to be 0%. To estimate the per cent resuspension for wind speeds between 0 and 13 ms^{-1} that did not have a measured resuspension rate, values were interpolated between the closest measured values (or assumed value at a wind speed of 0 ms^{-1}). For wind speeds above 13 ms^{-1}, the per cent resuspension rate for 13 ms^{-1} was used (Figure 3-5).

Wind speed ($m s^{-1}$)	Deposition Velocity (V_d) Average ($cm s^{-1}$)	Minimum ($cm s^{-1}$)	Maximum ($cm s^{-1}$)	Resuspension (%)
0	0.00	0.000	0.000	0.0
1	0.03	0.006	0.042	1.5
2	0.09	0.012	0.163	3.0
3	0.15	0.018	0.285	4.5
4	0.17	0.022	0.349	6.0
5	0.19	0.025	0.414	7.5
6	0.20	0.029	0.478	9.0
7	0.56	0.056	1.506	10.0
8	0.92	0.082	2.534	11.0
9	0.92	0.082	2.534	12.0
10	2.11	0.570	7.367	13.0
11	2.11	0.570	7.367	16.0
12	2.11	0.570	7.367	20.0
13	2.11	0.570	7.367	23.0

Figure 3-5 Deposition velocities and per cent resuspension per unit leaf area

Species	Wind Speed ($m s^{-1}$)				
	1	3	6	8.5[a]	10
Quercus petraea[b]		0.831	1.757	3.134	
Alnus glutinosa[b]		0.125	0.173	0.798	
Fraxinus excelsior[b]		0.178	0.383	0.725	
Acer pseudoplatanus[b]		0.042	0.197	0.344	
Psuedotsuga menziesii[b]		1.269	1.604	6.04	
Eucalyptus globulus[b]		0.018	0.029	0.082	
Ficus nitida[b]		0.041	0.098	0.234	
Pinus nigra[c]	0.13	1.15		19.24	28.05
Cupressocyparis x leylandii[c]	0.08	0.76		8.24	12.2
Acer campestre[c]	0.03	0.08		0.46	0.57
Sorbus intermedia[c]	0.04	0.39		1.82	2.11
Populus deltoides[c]	0.03	0.12		1.05	1.18
Pinus strobus[d]	0.0108				
Tsuga canadensis[d]	0.0193				
Tsuga japonica[d]	0.0058				
Picea abies[e]	0.0189				
Picea abies[e]	0.038				
Median	0.030	0.152	0.197	0.924	2.110
SE[f]	0.012	0.133	0.281	1.610	5.257
Maximum[g]	0.057	0.442	0.862	5.063	14.542
Minimum[h]	0.006	0.018	0.029	0.082	0.570

[a] combination of 8 and 9 $m s^{-1}$ wind speeds

[b] from Freer-smith (2004)

[c] from Beckett et al (2000)

[d] from Pullman (2009). Included particles up to 3.0 μm in diameter

[e] from Pullman (2009). Based on maximum and minimum of reported range. Included particles up to 3.8 μm in diameter.

[f] standard error

[g] based on median plus one standard error

[h] based on lowest recorded value for any species

Figure 3-6 Summary of average deposition velocities (cm/sec) of $PM_{2.5}$ from the literature per unit leaf area.

3.3.3.3 Air pollutant flux calculation for PM2.5

During non-precipitation periods, flux values of $PM_{2.5}$ are cumulated on leaves hourly, with a per cent of the accumulated $PM_{2.5}$ resuspended back to the atmosphere based on local wind speed. At time t, newly deposited PM2.5 flux as

$$f_t = V_{d,PM2.5,t} \times C_t \times 3600[gm^{-2}h^{-1}] \quad (23)$$

$$f_{min,t} = V_{d,PM2.5,min,t} \times C_t \times 3600[gm^{-2}h^{-1}] \quad (24)$$

$$f_{max,t} = V_{d,PM2.5,max,t} \times C_t \times 3600[gm^{-2}h^{-1}] \quad (25)$$

where:

F_t = $PM_{2.5}$ flux at time t

F_{min}=Minimum $PM_{2.5}$ flux at time t

F_{max}=Maximum $PM_{2.5}$ flux at time t

$V_{d, PM2.5, t}$= Deposition velocity at time t [ms^{-1}]

$V_{d, PM2.5, min, t}$ =Minimum deposition velocity at time t [ms^{-1}]

$V_{d, PM2.5, max, t}$ =Maximum deposition velocity at time t [ms^{-1}]

$C_{adj,t}$ = Air pollutant concentration at time t [gm^{-3}]

Resuspended amount of $PM_{2.5}$ at time t can be calculated as

$$R_t = (A_{t-1} + f_t) \times \frac{rr_t}{100} [gm^{-2}h^{-1}] \tag{26}$$

$$R_{min,t} = \left(A_{min,t-1} + f_{min,t}\right) \times \frac{rr_t}{100} [gm^{-2}h^{-1}] \tag{27}$$

$$R_{max,t} = \left(A_{max,t-1} + f_{max,t}\right) \times \frac{rr_t}{100} [gm^{-2}h^{-1}] \tag{28}$$

where:

R_t =$PM_{2.5}$ flux resuspended to atmosphere a time t

R_{min}= Minimum $PM_{2.5}$ flux resuspended to atmosphere at time t

R_{max}= Maximum $PM_{2.5}$ flux resuspended to atmosphere at time t

A_{t-1} =$PM_{2.5}$ accumulated on leaves at time t [$gm^{-2}h^{-1}$]

$A_{min,\ t-1}$=Minimum $PM_{2.5}$ accumulated on leaves at time t [$gm^{-2}h^{-1}$]

$A_{max,\ t-1}$ =Maximum $PM_{2.5}$ accumulated on leaves at time t [$gm^{-2}h^{-1}$]

rrt = $APM_{2.5}$ resuspension rate at time [%]

After $PM_{2.5}$ resuspended back to the atmosphere, the accumulated amount on leaves at time t can be calculated as

$$A_t = (A_{t-1} + f_t) - R_t [gm^{-2}h^{-1}] \tag{29}$$

$$A_{min,t} = \left(A_{min,t-1} + f_{min,t}\right) - R_{min,t} [gm^{-2}h^{-1}] \tag{30}$$

$$A_{max,t} = \left(A_{max,t-1} + f_{max,t}\right) - R_{max,t} [gm^{-2}h^{-1}] \tag{31}$$

after $PM_{2.5}$ resuspended back to the atmosphere, net $PM_{2.5}$ flux at time t can be calculated as

$$F_t = f_t - R_t[gm^{-2}h^{-1}] \quad (32)$$

$$F_{min,t} = f_{min,t} - R_{min,t}[gm^{-2}h^{-1}] \quad (33$$

$$F_{max,t} = f_{max,t} - R_{max,t}[gm^{-2}h^{-1}] \quad (34)$$

where:

F_t = Net $PM_{2.5}$ flux at time t

$F_{min,\ t}$=Minimum net $PM_{2.5}$ flux at time t

$F_{max,\ t}$=Maximum net $PM_{2.5}$ flux at time t

When the net flux is negative due to a large amount of resuspension and the absolute value of the net flux is greater than the total PM2.5 amount in the atmosphere

$$M_{total}[gm^{-2}h^{-1}] = C[gm^{-3}h^{-1}] \times mixing\ layer\ height[h] \quad (35)$$

The net flux is adjusted to be equal to -M [$gm^{-2}h^{-1}$].

Net flux can be negative in situations where a high amount of resuspension occurs. A flowchart explaining the steps and the input data required is provided in Figure 3-7

During times of precipitation, any $PM_{2.5}$ accumulated on leaves is assumed to exceed the maximum storage capacity on the leaf (0.2 mm x LAI) (Hirabayashi et al. 2015; Yang et al., 2008), the precipitation remains stored on the leaves, and there is no runoff from it, meaning no PM2.5 is washed off. If the amount of rainfall exceeds the leaf storage capacity, it is assumed to run off the leaf storage capacity; it is assumed to run off the leaf along with all of the accumulated Pm2.5. Thus, the resuspension, accumulation, and net flux of PM2.5 during these periods is calculated to be 0. (S.Hirabayashi, et al., 2015)

$PM_{2.5}$ was accumulated upon leaves and resuspended from leaves during non-precipitation periods. During precipitation events, the accumulated PM2.5 was assumed to be washed off to the ground surface depending upon the magnitude of the precipitation event (Pe in mm). As leaves capture about 0.2 mm of precipitation (Wang et al.,2008) before runoff the leaf, the total precipitation storage capacity (Ps in mm) of the canopy was calculated as 0.2x LAI. If Pe was greater than Ps, all particles were assumed to be removed from the leaves, and resuspension dropped to zero. When the Pe was less than Ps, no particles were removed from the leaves as there was no runoff from the leaves. After the rain stopped, PM2.5 began accumulating on and resuspending from leaves again. Water on the leaves after rain events was reduced hourly based on evaporation rates calculated from meteorological conditions. The annual flux to tree leaves was estimated as the total PM2.5 washed off leaves during the year plus the amount remaining on leaves at the end of the year. (Nowak, et al., 2013)

(Riondato, et al., 2020)

Hourly flux values to trees in the city (Eq.(1); µg m^{-2} h^{-1}) were multiplied by total leaf surface area (m^2) with hourly Vd based on local wind speed (Table3). Flux values were accumulated hourly with a per cent of the total accumulated $PM_{2.5}$ over the current and previous hours resuspended back to the atmosphere hourly based on local wind speed. (nello studio di (Nowak, et al., 2013)

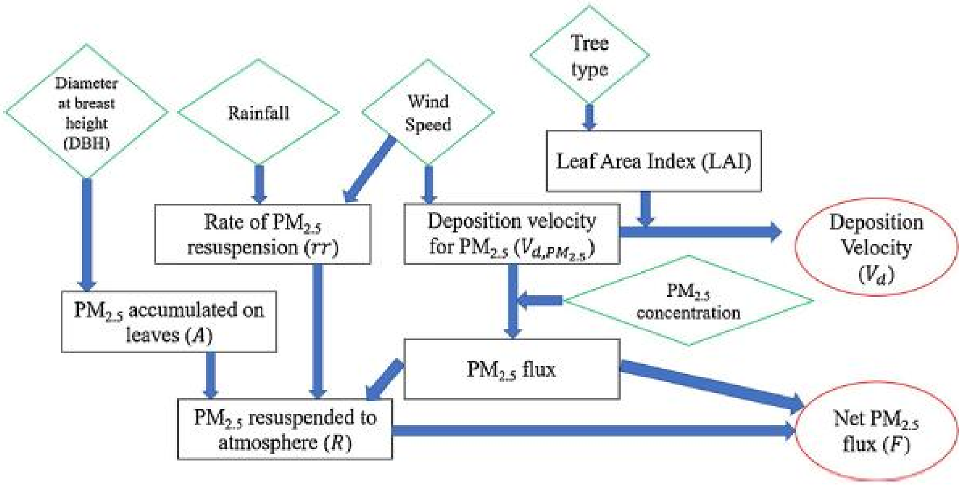

Figure 3-7 Flowchart showing steps in the i-Tree model to estimate the Deposition Velocity and Net PM2.5 flux. The inputs are provided using rhombus, the model estimated.

Hourly air quality Improvement per unit tree cover due to the dry deposition of air pollutants, I_{unit} [%] is calculated as

$$I_{unit} = \frac{F}{F + M_{total}} \times 100 \tag{36}$$

where:

F= pollutant flux [$gm^{-2}h^{-1}$]

M_{total} = Total air pollutant mass per unit tree cover

$$M_{total} = H \times C[gm^{-2}h^{-1}] \tag{37}$$

where:

H= Urban mixing height [m]

C= Air pollutant concentration [g $m^{-3}h^{-1}$]

for $PM_{2.5}$ if the net flux (F) is negative

$$I_{unit} = \frac{F}{M_{total}} \times 100 \tag{16}$$

Hourly air quality improvement for total tree cover, I_{total}[%]Is calculated as

$$I_{total=}\frac{F \times \frac{T_C}{100}}{F \times \frac{T_C}{100} + M_{total}} \times 100 \tag{17}$$

where:

T_c= Total tree cover in the city (%)

For $PM_{2.5}$, if F=-M_{total} and TC=100, the denominator in the ΔC equation become 0, and I_{total} becomes infinity.

To avoid this, the equation below should be used.

$$I_{total} = I_{unit} \times \frac{T_c}{100} \tag{18}$$

3.3.3.4 Air pollution concentration change calculation

Change in air pollutant concentration can be calculated as

$$\Delta C = \frac{C}{1 - \frac{I_{total}}{100}} - C \tag{19}$$

where:

ΔC = Air pollutant concentration change (ppm for CO, NO_2, SO_2, and O_3 and μgm^{-3} for PM_{10} and $PM_{2.5}$)

C = Air pollutant concentration (ppm for CO, NO_2, SO_2, and O_3 and μgm^{-3} for PM_{10} and $PM_{2.5}$)

The monetary value of pollution removal by trees is estimated using the median externality values for the United States for each pollutant (Murray et al. 1994, Ottinger et al. 1990) adjusted to 2007 dollars based on the producer price index (US Dept. of Labour 2008). The externality values are: CO=$1.407t^{-1}$, NO_2=$9.906t^{-1}$, PM_{10}=$6.614t^{-1}$, SO_2=$2.425t^{-1}$. The externality value for O_3 was set to equal the value for NO_2.

3.4 Theoretical foundations of i-Tree Eco.

AS mentioned in the previous paragraphs for calculating the deposition rate of PM2.5, I-Tree starts from the values derived from: (Beckett et al. 2000, Freer-Smith et al. 2004, Pullman 2009). All three works have the lowest common denominator, having obtained results using wind tunnels Measurements.

- (Beckett, et al., 2000)
- (Freer-Smith, et al., 2004)
- (Pullman, et al., 2009)

3.4.1 Particulate pollution capture by urban trees: effect of species and windspeed

They analyzed the effectiveness of five tree species-pine (*Pinus nigra var. Maritima*), cypress (*x Cupressocyparis leylandii*), maple (*Acer campestre*), whitebeam (*Sorbus intermedia*), poplar (*Populus deltoides x trichocarpa* '*Beaupreè*')-in capturing pollutant particles. The focus of the work reported herein is to quantify the relative effectiveness of contrasting species in particulate uptake, emphasising trees that are likely to be planted in urban areas. This was achieved by exposing them to NaCl droplets of approximately 1µm diameter at a range of windspeeds in two wind tunnels. The deposition velocity (V_g) and particle trapping efficiency (C_p) were calculated from these exposures. In addition, a variable dependent on foliage structure [Stokes number (*St*)] was correlated with *Cp* to gauge the effect of tree morphology on particle capture. Maximum Cp values ranged from 2.8% for *P.nigra*, to 0.12% and 0.06% for P.*trichocarpa x deltoides* and *A.campestre*, respectively.

	u (m s^{-1})	*P. nigra*	*C. leylandii*	*A. campestre*	*S. intermedia*	*P. trichocarpa* × *deltoides*
Mean V_g (cm s^{-1})	1	0.13 (0.02)	0.08 (0.0)	0.03 (0.02)	0.04 (0.02)	0.03 (0.0)
	3	1.15 (0.09)	0.76 (0.13)	0.08 (0.02)	0.39 (0.17)	0.12 (0.04)
	8	19.24 (3.65)	8.24 (2.1)	0.46 (0.11)	1.82 (0.9)	1.05 (0.08)
	10	28.05 (2.22)	12.2 (4.67)	0.57 (0.01)	2.11 (0.5)	1.18 (0.22)
Mean C_p (%)	1	0.13 (0.02)	0.08 (0.0)	0.02 (0.0)	0.04 (0.02)	0.03 (0.0)
	3	0.38 (0.03)	0.25 (0.04)	0.03 (0.01)	0.13 (0.06)	0.04 (0.01)
	8	2.41 (0.46)	1.03 (0.26)	0.06 (0.01)	0.23 (0.11)	0.13 (0.01)
	10	2.8 (0.22)	1.22 (0.47)	0.06 (0.01)	0.21 (0.05)	0.12 (0.02)

Figure 3-8 Mean values of deposition velocity (Vg) and capture efficiency (Cp) at a range of windspeeds (u) for trees exposed to particles in wind tunnels experiments.

The finer, more complex structure of the foliage of the two conifers (*P.nigra and C.leylandii*) explained their much greater effectiveness at capturing particles. Data from wind tunnel experiments were consistent with field measurements made on small groups of trees (Beckett, et al., 2000),

3.4.2 Capture of particulate pollution by trees: A comparison of species typical of semi-arid areas (*ficus nitida* and *eucalyptus globulus)* with *European and North American species)*

They present relative deposition velocities and capture efficiencies of five species used widely in the woodland of urban and periurban areas of Europe (*Quercus petraea* (oak), *Alnus glutinosa* (alder), *Fraxinus excelsior* (ash), *Acer pseudo-Platanus* (sycamore) and *Pseudotsuga menziesii* (Douglas fir)), and for two species, being used increasingly in semi-arid regions, (*Ficus nitida* (weeping fig) and *Eucalyptus globulus* (Eucalyptus)). These data are for species not previously worked on, and measurements were made at three windspeeds. Deposition velocities and capture efficiencies are compared with those published for other tree species, with the values of deposition velocity ranging from 0.1 to 0.3 cms^{-1} at 9 m s^{-1} windspeed (Freer-Smith, et al., 2004).

	μ $(ms)^{-1}$	*Q. petraea*	*A. glutinosa*	*F. excelsior*	*A. pseudo-platanus*	*P. menziesii*	*E. globulus*	*F. nitida*
Mean Vg_{rel} $(cm\ s)^{-1}$	3	0.831 (0.956)	0.125 (0.057)	0.178 (0.56)	0.042 (0.027)	1.269 (1.167)	0.018 (0.007)	0.041 (0.004)
	6	1.757 (2.582)	0.173 (0.055)	0.383 (0.124)	0.197 (0.123)	1.604 (0.668)	0.029 (0.005)	0.098 (0.024)
	9	3.134 (4.305)	0.798 (0.424)	0.725 (0.275)	0.344 (0.94)	6.04 (3.998)	0.082 (0.009)	0.234 (0.040)
Mean Cp (%)	3	0.277 (0.319)	0.042 (0.019)	0.059 (0.022)	0.014 (0.009)	0.423 (0.389)	0.006 (0.002)	0.014 (0.001)
	6	0.293 (0.430)	0.029 (0.009)	0.064 (0.021)	0.033 (0.021)	0.267 (0.111)	0.005 (0.001)	0.016 (0.004)
	9	0.348 (0.478)	0.089 (0.047)	0.081 (0.031)	0.038 (0.10)	0.671 (0.444)	0.009 (0.001)	0.026 (0.004)

Figure 3-9The effects of species and windspeed on the deposition velocities (Vgrel, cm s−1) and capture efficiencies (Cp, %) of the stems of five European broadleaved and one needle-leaved) and two semi-arid tree species (both broadleaved).

	μ $(m\ s^{-1})$	*Q. petraea*	*A. glutinosa*	*F. excelsior*	*A. pseudo-platanus*	*P. menziesii*	*E. globulus*	*F. nitida*
Mean Vg_{rel} $(cm\ s^{-1})$	3	0.276 (0.13)	0.079 (0.01)	0.248 (0.12)	0.336 (0.12)	0.010 (0.00)	0.066 (0.01)	0.384 (0.07)
	6	1.264 (0.53)	0.219 (0.04)	0.884 (0.13)	1.006 (0.02)	0.039 (0.01)	0.152 (0.03)	0.537 (0.11)
	9	2.909 (1.89)	0.355 (0.12)	1.158 (0.42)	1.468 (0.32)	0.088 (0.03)	0.324 (0.12)	1.286 (0.12)
		–	–	–				
Mean Cp (%)	3	0.092 (0.04)	0.026 (0.00)	0.083 (0.04)	0.112 (0.04)	0.003 (0.00)	0.022 (0.00)	0.128 (0.03)
	6	0.211 (0.09)	0.037 (0.00)	0.147 (0.02)	0.168 (0.00)	0.013 (0.00)	0.025 (0.00)	0.089 (0.02)
	9	0.323 (0.22)	0.039 (0.01)	0.129 (0.05)	0.163 (0.04)	0.009 (0.00)	0.036 (0.01)	0.143 (0.01)

Figure 3-10The effects of species and windspeed on the deposition velocities (Vgrel, cm s−1) and capture efficiencies (Cp, %) of the stems of five European and two semi-arid tree species.

The effects of windspeed on C_p and V_g are consistent with earlier wind tunnel data (K.P.Beckett, et al., 2000) and the theoretical understanding of particle uptake by foliage. The number of particles that strike an object rather than being diverted around it would be expected to increase as windspeed increases. Higher windspeeds particles with greater momentum will penetrate the boundary layer more effectively.

3.4.3 Conifer $PM_{2.5}$ deposition and resuspension

In this study, three conifer species were dosed with KNO_3 D_p 2.5µm particulates and exposed in a wind tunnel to winds of 6.5, 10, and 13 m/s for 5,10, or 20 minutes, to determine $PM_{2.5}$ resuspension rates. Deposition velocities were also determined over a range of PM concentrations., The three conifers chosen were Eastern White Pine (Pinus strobus), Japanese Yew (Taxus cuspidata), and Eastern Hemlock (Tsuga canadensis). These species are essential to the Northeast Atlantic region and represent a range of needle length and width within the conifers, range of needle length and width within three conifers, and a range of branch flexibility from rigid to supple determines its physical reaction to increasing wind speed. One of the objectives was to contribute to the USDA Forest Service's UFORE-D model by providing details of deposition and resuspension on specific tree species. Three conifers, Pinus strobus, Taxus cuspidate, and Tsuga canadensis, were dosed with KNO_3 particles in the wind tunnel to determine $PM_{3.0}$ V_d, a subset treated wind event in the wind tunnel or a wash off event, and particle removal rates were calculated. The result is in Figure 3-11

Species	Particle Diameter (µm)	Vd (cm/s)	Wind speed (m/s)	Author
Liriodendron tulipifera & Quercus rubra	0.7	0.056-0.56	Varies (outdoors)	(Wu et al., 1992)
Picea abies	3.8	0.0189 - 0.038	0.8 LAI = 6-11	Biel (2007)
Pinus strobus *Tsuga canadensis* *Taxus japonica*	3.0	0.0108 0.0193 0.0058	1.2	Pullman (2008)
Pseudotsuga menziesii	0.8	0.1-10	Varies (outdoors)	(Gallagher et al., 1997)
Pinus nigra	0.8	0.1	0.7	(Beckett et al., 2000b)
Pinus nigra	2	1.75 (rural) 6 (city park)	Varies (outdoors)	(Freer-Smith et al., 2005)

Figure 3-11 Velocity deposition for (Pullman 2009)

Pinus strobus has a V_d of 0.01 cm s-1, which is one order of magnitude less than that found with *Pinus nigra* in the wind tunnel at a slower wind speed, 0.1 cm^{s-1}, which is one order of magnitude smaller than Pinus nigra found out of doors in a woodlot (1.75 cms^{1}) or an urban park (Freer-smith 2005). These varieties do have different needle geometries, explaining the difference in V_d in various conditions.

3.5 Sensitivity Analysis

A model is an abstract representation of a system or process involving a certain degree of aggregation and exclusion. For any model, a critically important component is to assess the sensitivity of model output to model inputs and to develop estimators of the uncertainty of model outputs. Sensitivity analysis focuses on the change in model output values that result from changes in model input values. Overall, sensitivity analysis techniques can be roughly divided into global and local methods. Local methods typically involve variations of input parameters at one specific location (e.g., at one solution). They do not attempt to fully explore the simultaneous variation of all input variables across the entire input variable space.

Uncertainty typically exists in every component of a model, such as input data, model parameters, and model structure. The model building and calibration process (e.g., modelling assumptions, calibrating to datasets, communicating outputs, making decisions) could also introduce additional sources of uncertainty. In addition, applying models to the real world typically increases the magnitude of output uncertainty. Moreover, scale effects require re-verification of model structure and re-estimation of initial boundary conditions and coefficient thresholds. Given these issues, uncertainty analysis (UA) should be regarded as necessary as model output, and the assessment of model output uncertainty should be formally integrated with modelling practices. Decision-makers may alter their management decision with a better understanding of the uncertainty of model output. Uncertainty analysis should become a formal practice and necessary component of modelling exercises, especially for models that support decision-making and policy-formation.

The elements on which the sensitivity analyses have been concentrated are:

- Input data, sampling methods, model
- Input (low Concentration measurements)

In the first case, the consideration is made on global sensitivity analysis while in the seconds case on a local sensitivity analysis. Input data, sampling methods, model

In a study produced by (Lin, et al., 2020) , Nowak one of I-Tree's creators and developers. It was made through an uncertainty assessment for I-Tree Eco. Bootstrap and Monte Carlo simulation were employed to explore the uncertainty of I-Tree Eco. They assess the uncertainties associated with input data, sampling methods and models throughout the processes of urban forest structure and function quantification and aggregate the three sources of uncertainty to derive an estimator of total uncertainty. The uncertainty magnitude is expressed as the coefficient of variation by applying the uncertainty framework to a network of 15 cities across the United States. Sensitivity analyses were performed to investigate the relationships between Eco input and output variables and identify the most important parameters for estimating urban forest structure and function. For leaf area (LA) and leaf biomass (LB) estimators, crown height and width are essential variables. For instance, for BVOC emission estimators, leaf biomass, temperature, and photosynthetically active radiation (PAR) were most important; and for carbon storage and sequestration estimators, DBH was most important.

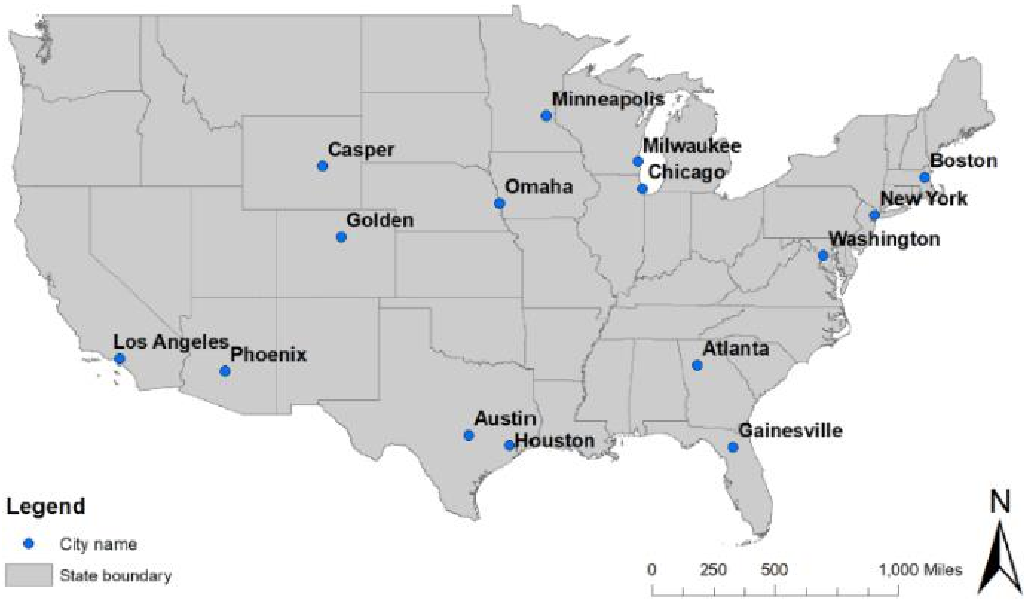

Figure 3-12 Cities utilized in the study of (Nowak, et al., 2021)

3.5.1 Leaf area

The uncertainty magnitudes for LA across 15 cities are displayed in **Errore. L'origine riferimento non è stata trovata.**. The uncertainty magnitude was expressed as CV values. For LA, the magnitudes of total uncertainty across 15 cities averaged 12.3% and ranged from 8.1% to 18.5%. Sampling uncertainty was the primary contributor to total uncertainty; input and model uncertainties had much smaller impacts. The mean magnitudes for both input and model uncertainties of LA were 0.7% and 2.0%, respectively, across all 15 cities, while sampling uncertainty averaged 12,2%. Unlike the magnitude of input and model uncertainties, which were relatively constant across the 15 cities, the importance of sampling uncertainty varied greatly, ranging from 8.0% (Chicago, IL) to 18.5% (Austin, TX). To explore the variability pf sampling uncertainty as a function of the number of plots, they employed the data from Chicago (with 745 plots) and bootstrap resampled from 25 to 745 plots and calculated the sampling uncertainty accordingly (Figure 3-13)

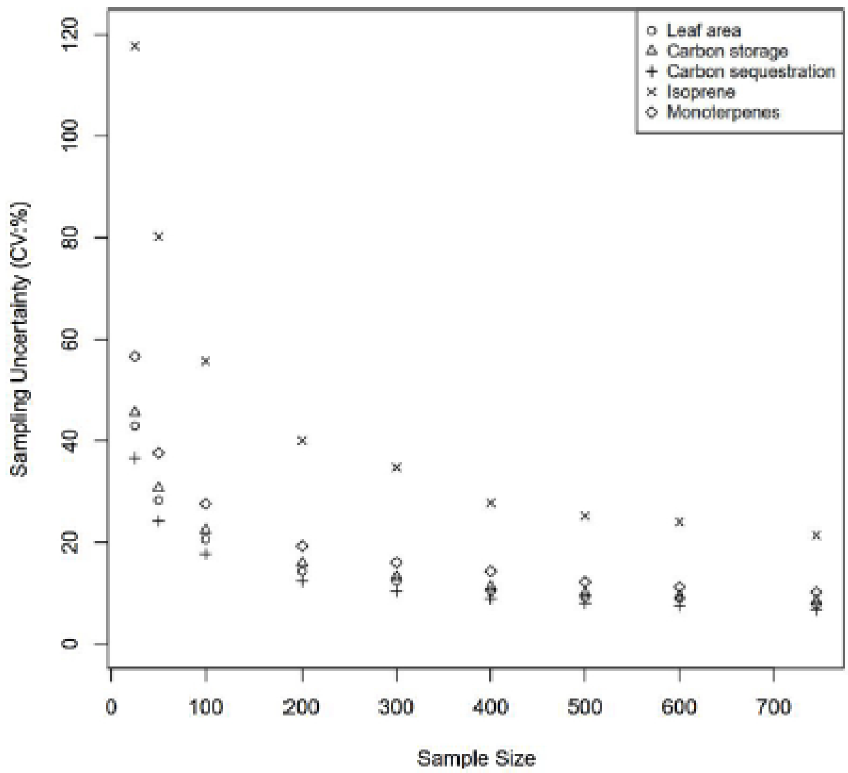

Figure 3-13 The effects of plot number on magnitudes of sampling uncertainty in Chicago

For LA, a decrease in sampling uncertainty from about 43% (25 plots) to 8% (745) plots was observed. Like results shown by (Nowak, et al., 2008), the sampling uncertainty decreased sharply within the first 200 plots and less so over 200 plots. Similar patterns were also observed for other Eco outputs.

They discovered that the two most likely ways to reduce estimator uncertainty are in the model inputs and sampling. While input uncertainty is relatively low, efforts to ensure accurate field data collection are essential. Errors in tree measurements (e.g., DBH and crown diameters) will affect results such as leaf area. They find that the average magnitude of total uncertainty across 15 cities is 12.3% for leaf area.

	Leaf area (CV: %)			
City, State	Input	Sampling	Model	Total
Atlanta, GA	0.4	9.2	0.9	9.3
Austin, TX	1.6	18.5	0.5	18.5
Boston, MA	0.5	9.7	1.6	9.9
Casper, WY	1.1	15.2	2.4	15.4
Chicago, IL	0.4	8.0	1.1	8.1
Gainesville, FL	0.6	13.5	1.6	13.6
Golden, CO	1.1	17.1	4.0	17.6
Houston, TX	0.3	9.4	1.0	9.5
Los Angeles, CA	0.7	8.9	3.7	9.7
Milwaukee, WI	0.6	9.8	1.7	9.9
Minneapolis, MN	0.9	11.4	2.2	11.7
New York, NY	0.7	11.0	1.4	11.3
Omaha, NE	0.6	11.8	1.3	11.9
Phoenix, AZ	0.8	13.0	3.7	13.5
Washington, DC	0.7	14.1	2.4	14.3
Mean	0.7	12.0	2.0	12.3
Standard deviation	0.3	3.1	1.1	3.1

Figure 3-14 Uncertainty magnitude of leaf area

Reducing the sampling uncertainty will reduce total tension. Still, the cost of reducing this uncertainty with more plots and the relatively low uncertainty of about 12% for many estimators will likely limit expanded field data collection to reduce uncertainty. Increasing the plot totals from 10 to 200 reduces uncertainty from around 50 per cent to 12 per cent; adding 200 plots only reduces the uncertainty to about 8 per cent while likely doubling data collection costs. While reducing uncertainty needs to be considered as well as whether the uncertainty needs to be reduced.

A 12 % total uncertainty for many urban forest estimators is likely an acceptable level of luck for a population estimator. However, sub-population estimators (e.g., estimators for one species or within an individual land use) will have increased uncertainty due to increase sampling errors from a smaller sample size. If particular areas or species need to be assessed, the sampling strategy may need to be modified to reduce estimator uncertainty. Individual tree management (e.g., street trees) estimators often require reduced uncertainty, and entire street tree populations are often inventoried (a census), reducing sampling error to zero. Users need to consider project goals, accuracy, uncertainty, and costs when developing data collection and analysis protocols.

It must be clarified that:

First, uncertainty magnitudes reported in this study are still believed to be conservative due to the omission of other factors that could increase output uncertainty.

Second, this study focuses on urban areas in the US, and the applicability of findings to other locales, especially outside the US, is uncertain (Lin, et al., 2020).

Previous expressions for open-grown trees were derived from a study made in 1996 by Nowak, one of the developers of I-Tree. The study's objective was to develop and compare regression equations to predict leaf area and leaf biomass of open-grown, deciduous urban trees based on dbh and crown parameters. In July 1992, data were collected from 54 healthy, open-grown park trees in Chicago, Illinois, explicitly selected for full tree crowns in excellent condition. The sampled trees included 10 American elm (Ulmus americana L.), ten green ash (Fraxinus pennsylvanica Marsh.), ten hackberry (Celtis occidentalis L.), ten honeylocusts (Gleditsua triacanthos L.), and 14 Norway maple (Acer platanoides L.). Data were collected on dbh, tree height, height to base of the live crown, and crown width. Nowak concluded that the regression equation based on tree crown parameters provide a more reliable means to estimate leaf-surface area and leaf biomass of open-growth deciduous trees than equations based on dbh. Additional research is needed to quantify how leaf area and leaf area, and leaf biomass of individual open-grown trees change based on tree condition, pruning and other factors that influence the total crown mass. (Nowak, 1996)

3.5.2 Input data (Difference in Pollution measurements)

The I-Tree Eco pollution model used in I-Tree Eco software is a limitation to consider spatial differences in air pollution occurring in the area analysed. This affects the estimated annual quantities of air pollutants absorbed by trees, as determined by the software, and thus lead to an inaccurate estimate of the economic value of that ecosystem service. A study was carried out by (Skzop, 2020) to evaluate the sensitivity of the I-Tree Eco (v6) pollution model to different pollution data inputs. The I-Tree Eco project for the street trees in Warsaw, Poland, was carried out, and the results analysed using the coefficient of variation (CV). The ability of trees to absorb pollutants depends mainly on the size of their leaf area (LA) and the concentration of these pollutants in the air. The study carried out allows one to compare the results obtained by the I-Tree Eco model, based on data retrieved from different air quality monitoring stations. At the same time, all the other factors, including the size of the leaf area, remain constant. The results indicate that the estimates are strongly influenced by the type of station from which the air pollution data was used for I-Tree Eco modelling.

The coefficient of variation (CV) shows relatively low variability (0.05) of the results obtained from stations of the same type ("urban background" type stations), $PM_{2.5}$(0.05) instead the coefficient of variation shows relatively high variability of results obtained from different station types, where the coefficient of variation recorded for $PM_{2.5}$ was between 0.24 and 0.27. The results show that the values obtained by employing the pollution concentration data derived from different monitoring stations may cause substantial differences in the values calculated by the I-Tree Eco pollution model. In terms of absolute numbers of pollutants being absorbed, these results show that a specific T. cordata tree growing in a traffic area (street with high traffic volume) in Warsaw can potentially absorb approximately 70% more $PM_{2.5}$ than a similar tree growing in an urban background area of the city (e.g., in city parks along local roads with low traffic volumes).

Therefore, the study shows that I-Tree Eco projects, including trees growing in areas with different pollution levels, will be substantially overestimated or underestimated if data from a single air quality monitoring station is used. Therefore, it is important to ensure that appropriate air pollution data are used for running a particular type of I-Tree Eco project for the accuracy of estimates. Data retrieved from an “urban background “station should be used when the project is for urban background areas and data retrieved from a “traffic “station when the project is for traffic areas. These hourly environmental data (e.g., meteorological data) are spatially limited in most landscapes but can vary substantially across landscapes. Efforts to obtain more spatially distributed data would help improve local estimators and reduce their uncertainty. However, given the practical and economic limitations in establishing more monitors, this limitation is not likely to be easily overcome. Model inputs will continue to rely on the best available local environmental data. (Szkop, 2020)

3.6 Limits and Uncertainties of I-Tree

The software was chosen "i-Tree" has, however, highlighted several limits that are exposed below:

- Theoretic basis wind measurement
- Difference between real and monitored values.
- Uncertainty due to considering only the leaf surface.
- Uncertainty due to crown light exposure
- Lack of input data
- Uncertainty due to the choice of the species

3.6.1 Theoretic basis wind measurement

The values of the deposition rate of the particles used inside I-Tree are based on data measured in the various studies already mentioned in the previous chapter, mainly using wind tunnels. Particle deposition research has employed the use of wind tunnels for a half-century to observe particle behaviour closely. However, it must be noted that airflow conditions in the wind tunnel contain an artefact of the design. In the natural settling, turbulence exists within the air mass structure. This is large-scale turbulence that begins as the wind picks up speed over rough surfaces and results in temporary wind speed maxima vortexes move through space. This wind tunnel does not have the size for large and complex turbulence structures to develop responsible for fluctuation in windspeed; instead, windspeed conditions are more consistent with small, turbulent structures.

The design research of (Pullman, et al., 2009) did not include an aspect of windspeed that does exist with regularity. Wind speed will increase to large gusts 1-3 seconds long that can be twice the average wind speed. These gusts are the most efficient at disrupting the soft boundary layer and will act to resuspend particles, as will a shift in wind direction, as sheltered particles will now have direct wind exposure. Neither of these aspects of the native setting was included in the study design. Therefore, resuspension could be slightly higher because of it. An extension of this research could study the same treatment conditions for 2-5 hours in the wind tunnel to examine the possibility of long-term resuspension trends more fully. The current wind tunnel's motor was limited to no longer than two continuous hours, preventing this study from being done on-site. (Pullman, et al., 2009)

Uncertainty due to turbulence

The concentration of $PM_{2.5}$ varies a lot throughout the day, with the intensity of the sources changing (see traffic intensity). Still, the value measured by the monitoring station is averaged over 24 hours. Moreover, within the urban context, the concentration of pollutants varies significantly along with the vertical profile of the trees. There is a study (Jin, et al., 2014) where a seasonal investigation was performed in six typical street canyons in the residential area of central Shanghai, which has been suffering from haze pollution while having large numbers of green streets. They monitored and measured $PM_{2.5}$ concentrations at five heights, structural parameters of street trees and weather. For tree-free street canyons, declining $PM_{2.5}$ concentrations were found with increasing altitude. However, in the presence of trees, the reduction rate of PM2.5 concentrations was less pronounced. In some cases, the concentrations even increased at the top of street canyons, indicating tree canopies are trapping $PM_{2.5}$. The presence of the barrier near the source leads to an increase in concentration and deposition. This is not considered by I-Tree software, and therefore in the present case study could lead to an understatement of the amount of Particulate matter deposited on the vegetation,

3.6.2 Difference between real and monitored values.

The software uses input values from monitoring stations that record parameters such as pollutant concentration and wind speed. These parameters do not consider the spatial variations that may occur, especially in huge areas, think that close to busy roads, the concentrations can be much higher than those that would be considered the average figure of a given site, for example, in the case of an urban centre, there may be significant differences between the centre and the suburbs or between the middle and the concentration within an urban canyon. The same applies to temporal variations. In the case of the concentration values of $PM_{2.5}$, annual values are taken into account seasonal fluctuations in the values, which often occur between the summer and winter seasons.

The same goes for the speed of the wind, the average values taken thanks to the monitoring stations for obvious practical reasons will always differ from the value have at the leaf surface and within the vegetative structure. There is also a problem with measuring the $V_{d;}$ measure deposition velocities used to calculate the average V_d are based on varying particle sizes with some particles greater than 2.5 μm (up to 3.8 μm), and particle size affects the deposition velocity. It is assumed that the measured deposition velocities represent the average for the particle distribution in the atmosphere.

3.6.3 Uncertainty due to not considering bark and another surface.

Another line of improvement should also be noted, which is the neglection of branch and bark surfaces in estimates of pollutant removal. While the deposition at these surfaces may be negligible for conifers with needles that densely cover twigs and canopy that shields stem from pollutants, it is considered at least for some deciduous trees. Neglecting this effect might lead to severe biases during winter. (Grote, et al., 2020)

3.6.4 Uncertainty due to crown light exposure.

Another important characterization is the degree of competition that a tree experience. This is expressed as “CLE (Crown Light Exposure)” in the I-Tree Eco model. Because educated investigators evaluate this parameter, it is expensive and remains subjective. As mentioned above, the I-Tree Eco requires information concerning the species and the stem diameter at breast height (DBH) as the input data. Additional data, including land use criteria, total tree height, crown size (height to live top, height to the crown base, crown width, and percentage of crown missing), crown health (dieback or condition), and competition status, can improve the model accuracy. Most of these input data are usually determined in the field by explicit visual inventories. This determination method is relatively easy to learn but remains subjective and prone to errors.

3.6.5 Uncertainties due to the lack of inputs data

I-Tree Eco v6.0 requires users to collect only two tree measurements (species and diameter at breast height or DBH) to complete an Eco project. This streamlined approach enables users with limited tree data to run an I-Tree Eco project; it has substantial limitations. The limitation of not collecting those highly recommended variables is that, without the actual data for each tree, the Eco model will use various approaches to fill in the missing variables. Some of these approaches use a default value, meaning all trees will be assigned the same value. Where defaults are not used, the model will use regression equations to fill in the other missing values. The regression equations used to estimate tree measurements, including total tree height, live tree height, and crown width, are selected based on the collected tree species data. No species-level equation exists. A genus-level equation is used, and so on up the taxonomic scale until an equation is found. These regression equations use the collected DBH data to predict the tree variables not measured for each tree. One of the caveats of using a regression equation (e.g., predicting tree height from DBH) is that the model will tend to indicate toward an average, meaning particularly tall or short trees will be underestimated or overestimated, respectively. This limitation is more prominent at the individual tree scale. For estimates of large population totals, the over-and underestimates are more likely to offset each other. However, this assumption may not truly depend on the population and equations used. The developers of the software strongly recommended that users collect:

- Land use
- Total tree height
- Crown size
  - Live Tree Height
  - Height to crown base
  - Crown width
  - Per cent crown missing
- Crown health
- Crown light exposure.

The accuracy of ecosystem service estimates can be improved significantly by providing these highly recommended tree measurements. The model outputs will better capture the structure and function of the urban forest in the study area. (USDA, 2020)

3.6.6 Uncertainty due to the choice of the species

In I-Tree, species definition is basic information on which many properties depend. Misclassifications of tree species can lead to significant deviations in estimates of ecosystem impacts.

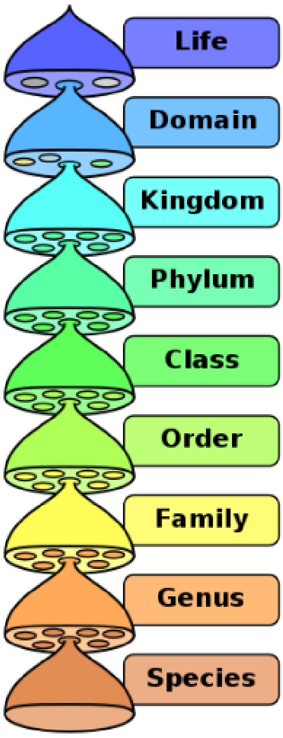

Figure 3-15 The hierarchy of biological classification's

A genus contains one or more species. For example, Quercus is the genus, and the *Quercus acerifolia* (maple-leaved oak), *Quercus petraea* (Rovere) are the species. The Species characterization data are essential for I-Tree Eco initialization because these data define the basic parameters used for calculating all ecosystem services (e.g., leaf area (LA)). If the species information is not available, the I-Tree Eco model uses values defined by the genus, family, or type (evergreen/deciduous), as explained in the chapter previous. This may be particularly problematic if the model is applied to regions other than the U.S.

The parameters were designed in the study (Pace, et al., 2018), it was analysed how Leaf Area calculations and, therefore, $PM_{2.5}$ deposition calculations are affected depending on whether the data from the specific species, the gene to which it belongs or the data from the dominant species in that area are used. Therefore, in that study, it was introduced a degree of uncertainty in species definition based on either imperfect knowledge-as is often the case with species in areas outside the original model development region (genus-specific parametrization)-or what can reasonably be derived from remote sensing measures (dominant species parametrization). The study shows that the total leaf area LA in the "genus-specific" simulation was approximately 5% lower than in the "species-specific" simulation, with slightly reduced pollution removal. This reflects the similarity between species and genus-based parameters, exhibiting the almost linear scaling of LA and deposition in I-Tree Eco.

A promising approach to achieve an automated initialization is applying remote sensing methods, which has been attempted in recent investigations. However, because of the complexity associated with urban areas (e.g., the high spectral similarity of vegetation types or overlooked small trees in high-density stand), initializations using remote sensing data have an inevitable degree of uncertainty concerning species differentiation. Additionally, it should be considered that most urban trees are deciduous. This creates difficulties in species distinction because the photogrammetric interpretation of aerial photographs generally allows only the separation of the evergreen deciduous trees, particularly when the plant species diversity is as high as that in the urban context. Hence, it is desirable to define I-Tree Eco initialization for species, size, and composition of each tree using cost-effective and objective methods, particularly when large areas are concerned. (Pace, et al., 2018). Measure deposition velocities used to calculate the average V_d are based on varying particle sizes. Some particles greater than 2.5 µm (up to 3.8 µm) and particle size affect the deposition velocity. It is assumed that the measured deposition velocities represent the average for the particle distribution in the atmosphere. Future research and more detailed modelling may help overcome these current limitations.

4 CASE STUDY IMPLANT OF VEGETATION BARRIER ALONGSIDE HIGHWAY

The Cispadana Regional Highway is a project to build the first regional highway that has never been made in Italy. Its length is about 67 km and will connect the tollbooths of Reggiolo-Rolo on the A22 with that of Ferrara south on the A13. The route of this work will cross, with west-east direction, the north-east quadrant of the Emilian plain, crossing the provinces of Reggio Emilia, Modena and Ferrara and will be a viable alternative to the central axis of the Via Emilia Corridor (A1/A14).

Figure 4-1 The blue line represents the positioning of the project in the existing motorway route.

This study is a continuation of a work carried out by the “studio Progetto Ambiente Srl”, which has realized a technical-scientific study in response to the Technical Commission of VIA n.11, formulated as part of the VIA decree of 25/01/2017, which mentions:

“Further compensatory measures to reduce the daily concentration of PM10 should be defined, through a prior study on PM10 itself, based on which the green insertion project should be optimised for compensatory purposes. Such study and the relative compensatory measures will have to be replaced in the verification of compliance with MATTM.”

To deepen, as required by the prescription, the absorption effect, and therefore compensatory, offered by the green works- However it is necessary to concentrate the study on pollutant $PM_{2.5}$, the benchmark for studies on the uptake of the amounts of pollutants removed, as illustrated in (S.Hirabayashi, et al., 2015)

$PM_{2.5}$ is well representative of dust emissions associated with the operation of a transport infrastructure, as indicated in the introduction of “1.A.3.b.i-iv Road Transport 2017 -EMEP/EEA air pollutant emission inventory guidebook – 2016”, which says:

“*All PM mass emission factors reported in this chapter refer to $PM_{2.5}$, as the coarse fraction (PM 2.5-10) is negligible in vehicle exhausts”.*

The coarse fraction of the PM_{10} considered as that relating to particles with diameter aerodynamics between 2.5µm and 10 µm is completely negligible about primary emissions provided of dust from discharges of vehicles in transit and that; therefore, the PM emissions provided by the Inventory relate is exclusively to $PM_{2.5}$. The coarser component (>2.5µm) contributes only for part-shares attributable to engine, brake, and road surface wear.

The Cispadana Regional Highway project is reviewed in this report regarding the number of inhalable dust emissions. By considering the additive term due to road traffic in operation and the subtractive term determined by the effect of dust capture and subsequent purification of the air implemented by the trees and shrubs Because of this, a methodological approach is used in this study to measure the removal capacity of fine particulates emitted by motorway traffic. Both by specific “filter interventions with air mitigation function foreseen in the Final Project of the Cispadana motorway, and the additional compensatory values planned for other reasons.

It should be specified that mitigation, interventions with the naturalistic, landscape, ecological, and agro-environmental function already planned in the project function for the atmosphere, can significantly contribute to dust absorption. The study, therefore, has the specific objective of quantifying the compensatory contributions of these interventions.

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4.1 Methodological approach

The project of the Cispadana Regional Highway is reviewed in terms of the quantitative balance of emissions of inhalable dust, considering the additive term due to the road traffic in operation and the subtractive term determined by the effect of dust capture and consequent purification of the air implanted by the vegetation (trees and Shrubs) envisaged by the draft green insertion. Primary dust emissions by discharges from transit vehicles are virtually all characterised by aerodynamic diameters of less than 2.5 µm. The coarser component (>2.5µm) contributes exclusively to the parts due to engine, brake, and road surface wear.

The presence of tree species along the motorway track can interact positively with the air due to removal processes. The quantities of Pm2.5 removed from the planted vegetation have been calculated known the characteristics as/quantitative of planned green interventions and notes the annual amounts of $PM_{2.5}$ directly issued by the infrastructure estimated with model COPERT V.

The study consists of three parts:

In the first, based on the available project data (linear development of the route, expected traffic flows, the composition of the vehicle fleet, operating speed), the annual quantities of PM2.5 directly emitted during the operation of the new road infrastructure are estimated. To do this, the COPERT V model is used.

In the second, through the calculation model i-Tree, note the qualitative and quantitative characteristics of the planned green interventions, both specific with mitigation function for “atmosphere and overall, are calculated the PM2.5 removed from the vegetation implanted.

In the third, by varying the input parameter of i-Tree and considering alternative scenarios, a brief sensitivity analysis is made, trying to understand how the planned green interventions' performance varies. By proposing some alternative scenarios.

4.2 Estimated emission of $PM_{2.5}$

The pollutant emissions of the circulating park depend on a series of characteristics, not always easily definable, which type of the vehicle, state of maintenance, speed, geometrical features of the route, style of guide, etc... For this reason, research programmes have been developed at the international level to identify reliable and easy-to-apply emission estimation methodologies. Due to the typological characteristics of the infrastructure analysed, reference was made to the hot emission factors, resulting substantially, cold and evaporative emissions. Emission factors are assessed using the COPERT V model, Computer Programme to calculate Emissions from Road Transport (http://emisia.com\). The analyses focus on the PM_{10} and consider the different types of vehicles (passenger cars, light commercial vehicles, heavy commercial vehicles), fuel (petrol, diesel, LPG, methane) and type approval of the various directive on vehicular emissions (Euro 0, I, II, III, IV, V, VI). Emissions associated with the wear and tear of brakes, tyres and road surfaces are also considered based on the emission coefficients proposed by the “EMEP/EEA air pollutant emission inventory guidebook-2016”. The composition of the Vehicular Park is hypothesized starting from the Medium Italian Vehicular Park provided by the Self-portrait ACI 2016.

The specific weight of the vehicle categories shall be weighed based on their actual average mileage. Table 4-1 are reported for macro types of vehicles, namely Cars, Light Commercial Vehicles (<3.5 tons) and Heavy Commercial Vehicles (>3.5 tons), the emission coefficients obtained as a function of the different transit speeds.

Speed [km/h]	**Emissions s $PM_{2.5}$ g/km*vehicle**		
	Automobile	**LDV**	**HDV**
30	**0.0286**	**0.0946**	**0.2582**
40	**0.0266**	**0.0866**	**0.2208**
50	**0.0253**	**0.0833**	**0.1996**
60	**0.0245**	**0.0846**	**0.1872**
70	**0.0244**	**0.0906**	**0.1801**
80	**0.0248**	**0.1012**	**0.1764**
90	**0.0259**	**0.1165**	**0.1754**
100	**0.0275**	**0.1364**	**0.1754**
110	**0.0298**	**0.1610**	**0.1754**
120	**0.0327**	**0.1610**	**0.1754**
130	**0.0363**	**0.1610**	**0.1754**

Table 4-1Emissions for different types of vehicle and speeds

4.2.1 Results of estimated emission

The emission coefficients can be calculated by the amount of dust ($PM_{2.5}$) emitted by the infrastructure under study by multiplying the unit emissions calculated in the previous paragraph by the vehicular flows and linear developments of the different road sections; last work paragraph. The vehicular flows to the scene of the plan of 2030e are derived from the Transport Analysis developed in the centre of the Definitive Plan and taken into account are relative to the average value between the average summer day and the average winter day. The following speeds shall be used for calculating the emission factors:

- Central axle: 130 km/h for passenger cars and LDV and 100 for HDV:
- Branches of junction and junctions: 40 km/h for all vehicles.

Finally, the weight of LDV on the total of light vehicles is calculated assuming a percentage of 7% value derived, in the absence of specific indication, the composition of the National Park 2016 provided in the "Autoritratto ACI 2016".

The calculation results are summarised in

Sector	Description	$PM_{2,5}$ Sector emission [kg/year]
1	Autostation Reggiolo-Rolo - Junction A22	4.634
2	From Junction A22 (excluded) to Exit S.Possidonio-Concordia-Mirandola (excluded)	7.495
3	From Exit S.Possidonio-Concordia-Mirandola to Exit S.Felice s/P-Finale Emilia (escluso)	9.398
4	From Exit S.Felice s/P-Finale Emilia to Exit di Cento (escluso)	8.325
5	From Exit di Cento a Exit di Poggio Renatico (escluso)	7.039
6	From Exit di Poggio Renatico to Junction A13 (esclusa)	7.640
7	From Junction A13 to Exit Ferrara Sud	3.874
		48.404

Table 4-2 Emissions of $PM_{2.5}$ for each sector.

4.3 Estimation of dust reduction caused by green mitigation interventions.

In areas most affected by pollution concentrations (junctions) due to input and output fluxes or due to acceleration/deceleration phenomena have been adopted types of plants that ensure high-efficiency mitigation against air quality. This objective will be pursued by planting trees with a dense planting scheme with air cleaning ability and using shrubs to saturate the spaces close to the ground of the highway. In the choice of the species, those which have an eco-physiological capacity for air depollution have been favoured (high physiological activity of primary production and high roughness of foliar systems and bark). These types of planting schemes used explicitly for this function of mitigation for air are:

- Type I1-Forest filter with air mitigation function
- Type I2 Shrub filter with air mitigation function

In addition to the interventions designed explicitly for mitigation, the effect of other types of interventions is determined. The overall assessment, which considers all the green plants planned in the project, were included the following typologies of planting scheme:

- Typology N1- Shrub hedge with ecological reconnection function
- Typology N2 Three-shrub hedge with ecological reconnection function
- Typology N3 Multi-specific shrub
- Typology N4 Plurispecific forest
- Typology P1 Multi-specific shrubby lines to conceal infrastructure.
- Typology P2 Arboreal shrubby rows for blinding infrastructure.
- Typology P3 Interventions of ornamental type
- Typology P4 Vines
- Typology P5 Arboreal row to effect for the requalification of the historic canals
- Typology P6 Arboreal row in prompt effect for the requalification of historical roads
- Typology P7 Arboreal row of shading
- Typology I1 Forest filter with air mitigation function
- Typology I2 Forest filter with air mitigation function
- Typology FT1 Longitudinal buffer strips to restore water quality.
- Typology FT2 Transverse buffer strips for water quality restoration
- Typology E1 Tree-shrub hedge for ecological reconnection of debris
- Typology I1-Forest filter with air mitigation function
- Typology I2-Shrub filter with air mitigation function

4.3.1 Calculation Methodology

4.3.1.1 Calculation Model: I-Tree Planting Calculator

The estimate of the amount of dust removed from the planned green interventions for the Cispadana Motorway is made using the "I-Tree Planting Calculator" model was designed to estimate the long-term environmental benefits of planting trees and shrubs. The focus of the calculation tool is on climate-changing gases, but other effects such as pollution can also be assessed. The information requested from the user is as follows:

- Arboreal species;
- Dimensions of trees at planting time (DBH-Diameter at Breast Height).
- Information on tree growth conditions.
- Estimated mortality (optional).
- The number of trees per configuration.
- Project duration (number of years).

The information provided by the model shall cover:

- Air pollutants captured and avoided.

The tool has been developed specifically for the US reality. It requires the insertion of the data that characterize the vegetational plant object of evaluation to identify the city that wants to carry out the assessments.

I-Tree software allows working on species that are typical of US territory. The area of Wichita in Kansas (USA) has been considered to be similar to the climatic regions crossed by the work (northern area of Emilia-Romagna), both from the climate point of view and for the concentration of $PM_{2.5}$, that are necessary from the particulate removal calculation phase. Therefore, it was required to evaluate the vegetative species suitable for the areas of realization of the infrastructure, where it was not possible to use the same species; it had to replace species that belonged to the same gene or family.

4.3.1.2 Analysis of climate analogy and pollution levels

The environmental parameters that influence the calculation tool are many and concern, especially the weather-climatic characteristics of the area, fundamental to identify the species that can be used and their growth rates, and pollution levels specific to the parameter under investigation. To use in Italy the calculation tool “i-Tree Planting Calculator”, it is, therefore, necessary to identify in the territory of the United States of America a city with weather features, climate, and pollution levels of $PM_{2.5}$ comparable to those in the field of study. Analysing the data available in “i-Tree Planting Calculator”, the area with the above characteristics is the Core Based Statistical Area (CBSA) of Wichita, KS.

Info	CBSA Wichita, KS	Municipalities interested in the project	
Source	Air Quality Statistics by City, 2016 – United States Environmental Protection Agency	Annual evaluations of background concentrations of PM10, ozone, PM2.5 e NO2 – ARPA Emilia Romagna – The year 2017	
	https://www.epa.gov/air-trends/air-quality-cities-and-counties	https://www.arpae.it/dettaglio_documento.asp?id=2988&idlivello=1692	
Parameter	98° Average daily percentile of Pm2.5	90° Average daily percentile of Pm2.5	
Value	20 µg/m^3	Cento	21 µg/m^3
		Concordia sulla Secchia	23 µg/m^3
		Ferrara	21 µg/m^3
		Finale Emilia	21 µg/m^3
		Medolla	22 µg/m^3
		Mirandola	22 µg/m^3
		Novi di Modena	23 µg/m^3
		Poggio Renatico	21 µg/m^3
		Reggiolo	24 µg/m^3
		Rolo	23 µg/m^3
		San Felice sul Panaro	22 µg/m^3
		San Possidonio	22 µg/m^3
		Sant'Agostino	21 µg/m^3

Table 4-3 Analogy between the $PM_{2.5}$ concentrations of the two areas

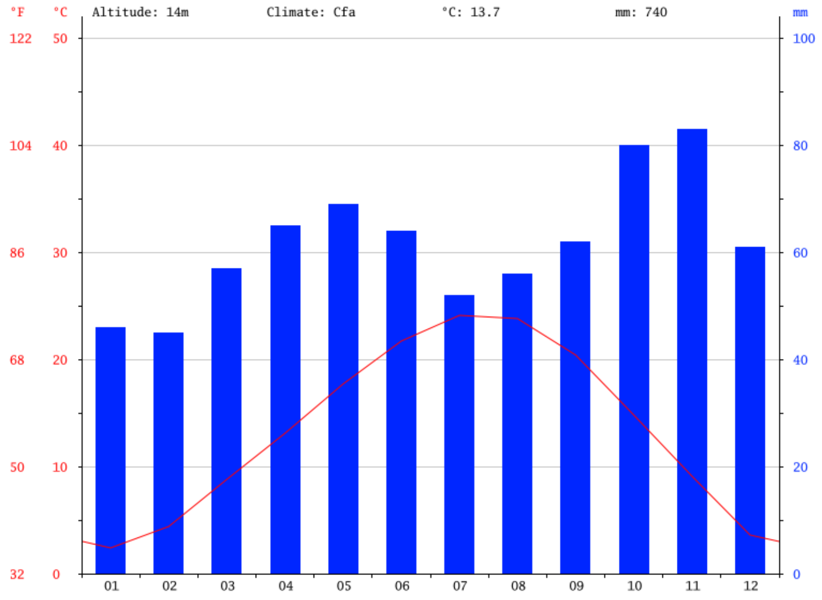
As can be seen from Table 4-3 the concentrations of $PM_{2.5}$ (pollutant under assessment) in the Core Based Statistical Area of Wichita and the municipalities affected by the Cispadana Regional Motorway route are reasonably similar. The comparison is made by considering, based on the available data, the 98 percentiles of the average daily concentrations for Wichita, equal to 20 $\mu g/m^3$ and the 90 percentiles for municipalities crossed by the Cispadana is between 21 and 24 $\mu g/m^3$. The presence of slightly higher levels of pollution within the scope of the study is, in any case, a precautionary measure it leads to an underestimation of the quantities of pollutant caught by the plants which are expected to be planted. The reduction of contaminants by green interventions is directly proportional to the concentration of the pollutant itself. By comparing the main climate parameters (source: https.|Climate-Data.org) reported in Table 4-4, Wichita has a climate very similar to that of Finale Emilia, representative location of the area on which the project insists, in both cases, the climate is classified as Cfa according to the Koppen Geiger classification. The rainfall and the average annual temperature is very similar.

The monthly data, reported in Table 4-4 and synthesized graphically in the pluviometric diagrams in Figure 4-2 the climatic analogies of the two localities, with minor differences related to a greater seasonal range of temperatures and rainfall in the North American resort. These differences, due to the uniqueness of the climate within the Mediterranean basin, which with its particular mildness dampens the climatic extremes, however, do not substantially change the ecology of the vegetation and the characteristics of the growing season, as evidenced also by the analogies in the spontaneous vegetation present in the two localities, afferent fitosociologically to the lowland oaks in both contexts (cf. “La vegetazione d’Italia” by Carlo Blasi e “A Classification of the Natural Vegetation of Kansas” by Chris L. Lauver, Kelly Kindsher, Don Faber-Langedoen, Rick Schneider).

FINALE EMILIA												
	Jen	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dic**
T average (°C)	2.4	4.4	8.8	13.1	17.7	21.7	24.1	23.8	20.4	14.8	9.1	3.6
T min (°C)	-0.4	1	4.6	8.5	12.7	16.4	18.6	18.4	15.5	10.5	5.9	1
T max (°C)	5.3	7.9	13.1	17.8	22.7	27.1	29.7	29.2	25.3	19.1	12.3	6.3
Precipititation (mm)	46	45	57	65	69	64	52	56	62	80	83	61
WICHITA, KS												
	Jen	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dic**
T average (°C)	-0.9	2.1	6.9	13.6	18.9	24	27.2	26.2	21.3	15	7	1.3
T min (°C)	-6.5	-4	0.4	7.1	12.8	17.9	20.9	19.8	15.1	8.5	1.1	-4
T max (°C)	4.7	8.2	13.5	20.1	25	30.2	33.6	32.7	27.6	21.6	13	6.7
Precipitation (mm)	19	25	54	68	107	115	93	82	92	67	39	29

Table 4-4 Monthly data of the two areas

FINALE EMILIA



WICHITA, KS

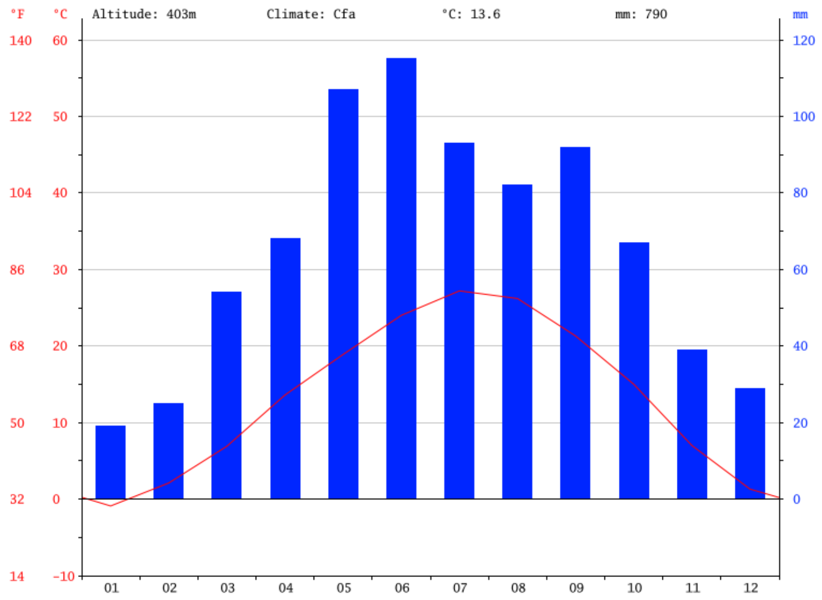


Figure 4-2 Pluviometric diagrams of the two areas

Analysis of the species to be used for evaluations.

The species used in the model were chosen to obtain the maximum ecological and Phyto-ecological similarities between the planned project plants along the Cispadana route and those contained in the I-Planting model of I-Tree. For the vegetational analogies of the two contexts, reference was made to “La Vegetazione d’Italia” by Carlo Blasi and “ A Classification of the Natural Vegetation of Kansas” by Chris L. Lauver Kelly Kindsher, Don Faber-Langedoen, Rick Schneider. Table 3-6, Table 3-7 contains:

- The list of species used for green interventions planned by the project.
- The species in the calculation model referred to.
- The reasons that led to the choice (Table 4-5):
- The removal potential for each sector in the first ten years
- Ther removal potential in grams of everyone in the first year of the implant:

1:	The same species was used in the project implantation.
2:	The average figure of species belonging to the same genus as the species planned in the project implant was used. The model includes this possibility as in some cases, especially among the shrubs, species belonging to the same genus have look and physiology very similar to each other (gen. Cornus, Ligustrum, Viburnum, Euonymus, etc..). Under similar ecological conditions, this similarity also persists for species with distinct geographic areas (analogy between North American and Eurasian areal species belonging to the same genus).
3:	As for note two, narrow the choice to the average figure of the shrubby species of the genus Prunus. This genus has both shrubby and arboreal species of different size classes; therefore, the analogy with the shrubby behaviour of the blackthorn has been used the average data of the only shrubby species of the genus.
4:	A species of the same genus as the species planned in the project installation has been used, having physiological and ecological characteristics as similar as possible. For example, the black cherry (Prunus serotina) in North America occupies the same ecological niche and has dimensions, bearing and characteristics practically identical to our wild cherry (Prunus avium).
5:	In the impossibility of using species as for the previous notes, a species of another genus has been chosen, but that occupies the same ecological niche. That has dimensions, posture and characteristics similar to that envisaged by the project. In this case, instead of the species of the genus Rosa, which are typically part of the shrubby layer of the oaks and in the general of the flatlands of the Po Valley, but are not present in the United States, a typical shrub of the shrub layer of the American oak woods has been used: the Asimina (Asimina triloba).

Table 4-5 Reasons for the choice of the species

Project species	Species utilized. in I-Tree	Note	Capture potential	
			First ten years [g/10 years]	1° year [g/year]
First magnitude trees				
Farnia (*Quercus robur*)	Farnia (*Quercus robur*)	1	32	0.6
Pioppo bianco (*Populus alba*)	Pioppo bianco (*Populus alba*)	1	21	0.3
Ciliegio selvatico / ciliegio (*Prunus avium*)	Ciliegio nero (*Prunus serotina*)	4	31	0.3
Frassino maggiore (*Fraxinus excelsior*)	Frassino maggiore (*Fraxinus excelsior*)	1	26	0.7
Salice bianco (*Salix alba*)	*Salix* species	2	21	0.6
Pioppo nero (*Populus nigra*)	Pioppo nero (*Populus nigra*)	1	17	0.2
Second magnitude trees				
Pero selvatico (*Pyrus pyraster*)	*Pyrus* species	2	13	0.5
Carpino bianco / carpino (*Carpinus betulus*)	Carpino bianco (*Carpinus betulus*)	1	26	0.7
Olmo minore (*Ulmus minor*)	*Ulmus* species	2	19	0.4
Frassino ossifillo (*Fraxinus oxycarpa*)	Frassino ossifillo (*Fraxinus oxycarpa*)	1	22	0.5
Ontano (*Alnus glutinosa*)	Ontano (*Alnus glutinosa*)	1	37	0.5
Third magnitude trees				
Acero Campestre (*Acer campestre*)	Acero campestre (*Acer campestre*)	1	14	0.4
Ciavardello (*Sorbus torminalis*)	*Sorbus alnifolia*	4	13.9	0.4
Melo selvatico (*Malus sylvestris*)	*Malus* species	2	12.6	0.5
Big shrubs				
Corniolo (*Cornus mas*)	*Cornus* species	2	7.5	0.3
Lantana (*Viburnum lantana*)	*Viburnum* species	2	8	0.6
Fusaggine (*Euonymus europeus*)	*Euonymus* species	2	9.5	0.5
Spino Cervino (*Rhamnus catharticus*)	Spino Cervino (*Rhamnus catharticus*)	1	8.9	0.6
Frangola (*Rhamnus frangula*)	Spino Cervino (*Rhamnus catharticus*)	4	8.9	0.6

Table 4-6 Comparison between project species and species used.

PROJECT SPECIES	UTILIZED SPECIES in i-Tree	Note	CAPTURE POTENTIAL	
			first ten years [g/10 years]	1° year [g/year]
Little shrubs				
Prugnolo (*Prunus spinosa*)	*Prunus* shrubs species	3	13	0.55
Ligustro (*Ligustrum vulgare*)	*Ligustrum* species	2	14	0.47
Rosa canina (*Rosa canina*)	Asimina (*Asimina triloba*)	5	15	0.95
Sanguinello (*Cornus sanguinea*)	*Cornus* species	2	17	0.525
Pallon di maggio (*Viburnum opulus*)	*Viburnum* species	2	10	0.925
Rosa selvatica (*Rosa arvensis*)	Asimina (*Asimina triloba*)	5	15	0.95
Salice da ceste (*Salix triandra*)	*Salix* species	2	11	0.3
Ready to go species				
Pioppo bianco (*Populus alba*)	Pioppo bianco (*Populus alba*)	1	29	0.65
Salice bianco (*Salix alba*)	*Salix* species	2	29	1.2
Farnia (*Quercus robur*)	Farnia (*Quercus robur*)	1	53	1.65
Frassino maggiore (*Fraxinus excelsior*)	Frassino maggiore (*Fraxinus excelsior*)	1	41	1.65

Table 4-7 Comparison between project species and species used

4.3.1.3 Project data used.

The estimation of the amount of dust removed from the green interventions planned for the Cispadana motorway route is made considering the following hypotheses:

- Duration of the planting: 10 years; this duration does not refer to the actual life of the trees planted but represents a reasonable time horizon to carry out the assessments covered by this technical report.
- Mortality: 10%, this value is reasonably representative of physiological mortality in a context that requires careful management and above all, in the first years the substitution of the fallacies: the maintenance plan in the first five years provides for the replacement of the fallacies with specimens at the same level of growth as those already present.
- Diameters of the essences implanted: plants to the ready effect of 8 cm (given design), first size 4 cm, second and third size 3 cm, shrubs 1 cm
- Exposure to sunlight: full sun
- Tree condition: Excellent.

The number of green implants for the different typologies of each sector indicates in Table 4-8.

TYPOLOGY	SECTOR 1	SECTOR 2	SECTOR 3	SECTOR 4	SECTOR 5	SECTOR 6	SECTOR 7
N1	81	231	318	224	382	554	53
N2	20	2	83	58	113	119	15
N3	60	836	767	524	535	978	0
N4	140	300	200	111	98	104	0
P-1	1491	4056	5097	4590	3460	1463	3482
P-2	108	91	532	174	1819	420	88
P-3	160	0	52	14	67	236	132
P-5	0	150	282	0	38	223	0
P-6	0	0	117	0	29	39	0
P-7	11	0	17	15	14	14	0
I-1	746	0	0	81	34	28	362
I-2	145	0	16	0	37	79	26
FT-1	0	281	0	0	0	0	0
FT-2	0	715	0	0	0	0	0
E-1	0	0	0	178	922	0	0

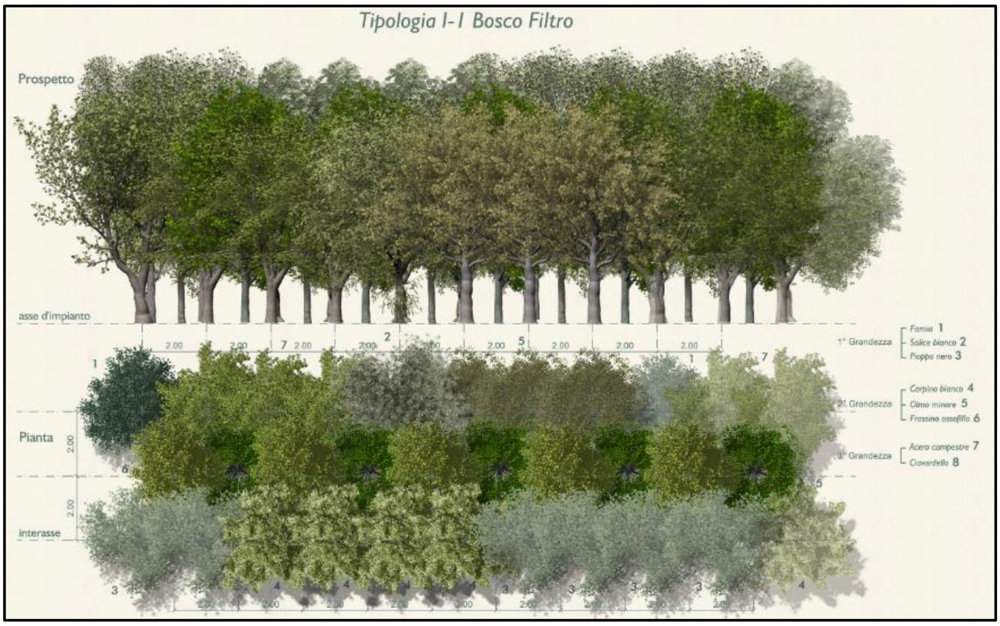
Table 4-8 Number of green implants for each typology and each sector

4.3.1.4 Estimations of removal potential by type of implant

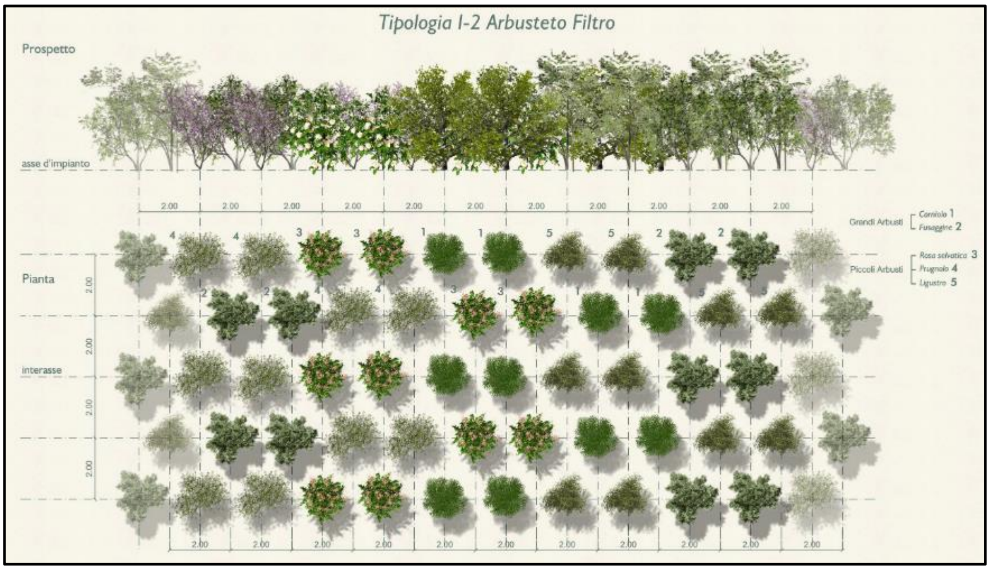
The results of the evaluations carried out for each of the types of planned plant are summarised in the following fact sheets describing the composition of the plant and reporting the removal potential to the first year and in the first ten years of life.

For practical reasons, only I1 and I2 are illustrated here. The other interventions are in the appendix.

- N1(Figure 6-1);
- N2(Figure 6-2);
- N3(Figure 6-3);
- N4(Figure 6-4);
- P1;(Figure 6-5);
- P2;(Figure 6-6);
- P3;(Figure 6-7);
- P5;(Figure 6-8);
- P6;(Figure 6-9);
- P7;(Figure 6-10);
- FT-1;(Figure 6-11);
- FT2(Figure 6-12) ;
- E1(Figure 6-13);

INTERVENTION TYPE I-1			Dimension: 72 m²		
					
Composition					
Specie	N.	Specie	N.	Specie	N.
Corniolo	10				
Fusaggine	10				
Rosa Selvatica	10				
Prugnolo	10				
Ligustro	10				
Capture potential					
First ten years (kg/10 years)			First-year (kg/year)		
0.510			**0.012**		

INTERVENTION TYPE I-2	Dimension: 144 m²



Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Farnia	1	Frassino Ossofillo	5		
Salice Bianco	1	Acero Campestre	3		
Pioppo Nero	4	Ciaverdello	3		
Carpino Bianco	4				
Olmo Minore	5				

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.535	**0.015**

Most of these interventions I1 and I2 (60%) are placed in the first section, near the connection with “A22 Modena-Brennero”, a place that is expected to be characterized by high traffic. The following images were taken from the document:“3770_PD_0_000_0MA00_0_MA_P5_01_A_” in “Docmenti di Procedura di VIA”.

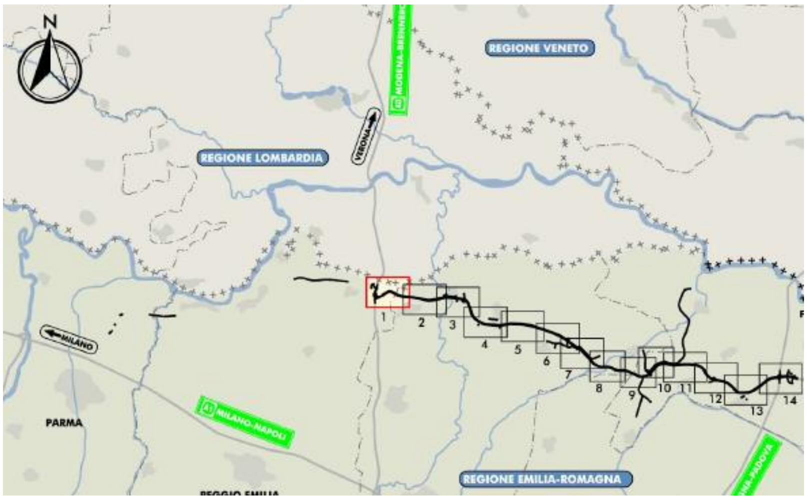


Figure 4-3 Position of Interconnection

Figure 4-4 Project simulation of the positioning of the green intervention in Junction of Autostrada Regionale Cispadana with “A22 Modena-Brennero”, there are the comparison between the actual and the future condition.

The interventions visible in Figure 4-4 are illustrated in the Figure 4-5;Figure 4-6.

Figure 4-5 Picture from the project reporting the position and the type of interventions in Interconnection with A22.

Zoom in of: Figure 4-6:

Figure 4-6 Zoom in of Picture from the project reporting the position and the type of interventions in Interconnection with A22. Inside the picture is possible to distinguish the different type of interventions.

4.4 Results

4.4.1 Mitigation intervention (I1 and I2)

Calculation of the emissions of $PM_{2.5}$ determined by the vehicular traffic and the quantities of $PM_{2.5}$ removed from the green interventions provided for by the Final Project along the motorway route allow to make an overall environmental balance. Note the amounts of $PM_{2.5}$ that different plant types allow to remove and note their numerical incidence in a different sector; it is possible to quantify the effect of $PM_{2.5}$ capture associated with green interventions planned for the various sectors of the motorway.

Note the quantities of $PM_{2.5}$ that the different types of installation allow to remove and note their numerical incidence in a different sector; it is possible to quantify the effect of $PM_{2.5}$ associated with green interventions planned for the different sections of the motorway already identified in Table 4-8. The calculations for the two air mitigation plants are given in Table 4-9; Table 4-10, in which, for each sector, are summarised the number of $PM_{2.5}$ removed in the first ten years of the implants' life.

	SECTOR 1	SECTOR 2	SECTOR 3	SECTOR 4	SECTOR 5	SECTOR 6	SECTOR 7
I1	746	0	0	81	34	28	362
I2	145	0	16	0	37	79	26

Table 4-9 Planting scheme planned for each sector.

	SECTOR 1	SECTOR 2	SECTOR 3	SECTOR 4	SECTOR 5	SECTOR 6	SECTOR 7
I1	381	0	0	41	17	14	185
I2	78	0	9	0	20	42	14
$PM_{2,5}$ REMOVED IN THE FIRST TEN YEARS [kg/10 years]	458	0	9	41	37	57	199

Table 4-10 Overall $PM_{2.5}$ capture the balance of the planned filter interventions in support of the Highway for the first ten years of facilities.

The average annual capture data is helpful for comparison but, at the same time, has no physical feedback, as the purification capacity of green intervention is directly related to their growth and is therefore minimal in the first year and increasing over time.

Figure 4-7 $PM_{2.5}$ removed yearly by the filter interventions in each sector[average yearly data].

The calculation of $PM_{2.5}$ emissions caused by vehicular traffic and the quantities of $PM_{2.5}$ removed from the green interventions planned by the Final project along the motorway allow to carry out an overall environmental balance.

The comparison between the emissive term and the term “capture” is shown in Table 4-11. For each motorway section, the annual emissions of $PM_{2.5}$ of the infrastructure and the quantities captured on average year from the only intervention’s “filter” are considered within the time horizon considered in the analyses.

	Highway Sector	Emissions $PM_{2.5}$ [kg/year]	Capture $PM_{2.5}$_Filter intervention [Kg/year]	Capture[%]
1	Autostation Reggiolo-Rolo - Junction A22	4633,7	45,8	-1,0%
2	From Junction A22 (excluded) to exit S. Possidonio-Concordia-Mirandola (excluded)	7494,8	0,0	0,0%
3	From exit S. Possidonio-Concordia-Mirandola to exit S. Felice s/P-Finale Emilia (excluded)	9398,2	0,9	0,0%
4	From exit S.Felice s/P-Finale Emilia to Exit of Cento (excluded)	8325,1	4,1	0,0%
5	From Exit of Cento to exit Poggio Renatico (excluded)	7038,5	3,7	-0,1%
6	From exit of Poggio Renatico to Junction A13 (excluded)	7639,8	5,7	-0,1%
7	From junction of A13 to exit Ferrara Sud	3873,7	19,9	-0,5%
	TOTAL BALANCE	**48403,8**	**80,1**	**-0,2%**

Table 4-11 Overall balance PM2.5(Infrastructure emissions-capture green operas) for air filter intervention

The evaluations show a potential reduction of the pollutant load between-0.1% and -1.0%. Although it is a relatively low value, it is necessary to consider that this type of intervention “filter” has been provided at junctions and areas with higher flows, therefore aimed at local emissions compensation, which if compared to the length significance of the different routes is contained.

4.4.2 All green interventions

Calculations are given in Table 4-12 which, for each planned motorway sector, are summarised the $PM_{2.5}$ removed for each typology of the implant and the amount of $PM_{2.5}$ removed in the first ten years of the life of the implant implants.

TYPE	$PM_{2,5}$ REMOVED [kg/10 years]	NUMBER of INTERVENTION FOR EACH SECTOR						
		S 1	S2	S 3	S 4	S 5	S 6	S 7
N1	0,208	81	231	318	224	382	554	53
N2	0,439	20	2	83	58	113	119	15
N3	0,158	60	836	767	524	535	978	0
N4	0,513	140	300	200	111	98	104	0
P-1	0,099	1491	4056	5097	4590	3460	1463	3482
P-2	0,192	108	91	532	174	1819	420	88
P-3	0,369	160	0	52	14	67	236	132
P-5	0,156	0	150	282	0	38	223	0
P-6	0,208	0	0	117	0	29	39	0
P-7	0,208	11	0	17	15	14	14	0
I-1	0,510	746	0	0	81	34	28	362
I-2	0,535	145	0	16	0	37	79	26
FT-1	0,510	0	281	0	0	0	0	0
FT-2	0,330	0	715	0	0	0	0	0
E-1	0,297	0	0	0	178	922	0	0
$PM_{2,5}$ REMOVED in the first ten years[kg]		**796**	**1159**	**1035**	**804**	**1309**	**791**	**628**

Table 4-12 $PM_{2.5}$ removed for each type of intervention, a number of interventions for each sector and total $PM_{2.5}$ drawn for each sector.

The comparison between the emissive term and the term “catch” is given in recital, for each motorway sector, the annual emissions of $PM_{2.5}$ of the infrastructure and the amounts caught by green interventions expected on average each year 10-year horizon considered in the analyses.

Highway Sector		Emissions $PM_{2.5}$ [kg/year]	Capture $PM_{2.5}$ [kg/year]	Capture[%]
1	Autostation Reggiolo-Rolo - Junction A22	4633,7	79,6	-1,7%
2	From Junction A22 (exclude) to exit S.Possidonio-Concordia-Mirandola (escluso)	7494,8	115,9	-1.5%
3	From exit S. Possidonio-Concordia-Mirandola to exit S. Felice s/P-Finale Emilia (exclude)	9398,2	103,5	-1.1%
4	From exit S.Felice s/P-Finale Emilia to Exit of Cento (excluded)	8325,1	80,4	-1.0%
5	From Exit of Cento to exit Poggio Renatico (excluded)	7038,5	130,9	-1.9%
6	From exit of Poggio Renatico to Junction A13 (excluded)	7639,8	79,1	-1.0%
7	From junction of A13 to exit Ferrara Sud	3873,7	62,8	-1.6%
	TOTAL BALANCE	**48403,8**	**652,2**	**-1,3%**

Table 4-13 Overall balance $PM_{2.5}$ Infrastructure emissions-capture green operas

4.4.3 Sensitivity analysis of planting scheme

I-Tree Planting Calculator allows inserting several parameters, including:

- Tree Mortality over Project Lifetime(%)
- Exposure to Sunlight
- Condition of the trees or shrubs (Excellent, Good, etc.)
- Choice of the species
- Dbh (Diameter at breast height, 1.37m).

In this section, it has been tested how different variables influence the capture potential.

4.4.3.1 Influence of "Tree Mortality Rate"

The mortality rate indicates the percentage of species that will reach death in the entire lifetime project. The project data was obtained using a mortality rate of 10%; so keeping the other parameters such as "tree condition" and " exposure to sunlight" unchanged, and using mortality rates of 30%,60%,90% the results reported in (Table 4-14).

TYPE	$PM_{2,5}$ REMOVED [kg/10 years]	$PM_{2,5}$ REMOVED 30%mort. [kg/10 years]	$PM_{2,5}$ REMOVED 60%mort. [kg/10 years]	$PM_{2,5}$ REMOVED 90%mort. [kg/10 years]
N1	0,208	0,184	0,153	0,127
N2	0,439	0,389	0,322	0,268
N3	0,158	0,140	0,117	0,097
N4	0,513	0,454	0,377	0,314
P-1	0,099	0,088	0,073	0,061
P-2	0,192	0,170	0,141	0,117
P-3	0,369	0,326	0,272	0,225
P-5	0,156	0,138	0,116	0,097
P-6	0,208	0,185	0,155	0,130
P-7	0,208	0,185	0,153	0,127
I-1	0,597	0,451	0,155	0,130
I-2	0,535	0,474	0,393	0,374
FT-1	0,510	0,474	0,393	0,326
FT-2	0,330	0,451	0,374	0,310
E-1	0,297	0,292	0,241	0,200

Table 4-14 $PM_{2.5}$ removed for each sector and each type, in different conditions of tree mortality rate.

This data is multiplied for the number of interventions for each type in each sector reported in (Table 4-8). , the results are reported in Table 4-15.

Sector	PM 2.5 removed in fist ten years_10% Mortality [kg/10 years]	PM 2.5 removed in fist ten years_30% Mortality [kg/10 years]	PM 2.5 removed in fist ten years_60% Mortality [kg/10 years]	PM 2.5 removed in fist ten years_90% Mortality [kg/10 years]
1	796	703	584	492
2	1159	1030	856	711
3	1035	914	761	634
4	804	715	595	494
5	1309	1183	983	818
6	791	700	583	488
7	628	554	461	384
Total [kg/10 years]	**6522**	**5798**	**4823**	**4019**
Δ[%]	-	-11%	-29%	-52%

Table 4-15 $PM_{2.5}$ removed each sector for four different tree mortality rates (10%,30%,60%,90%); in the last two rows, total removal with different configuration and percentage variation respects the first value.

The results of Table 4-15 are illustrated in Figure 4-8.

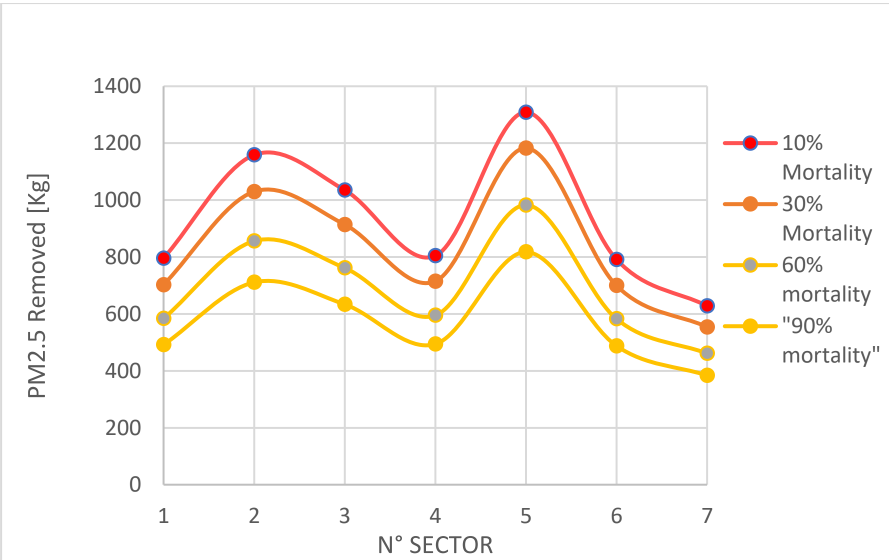


Figure 4-8 Capture performance of each sector for four different Mortality rates.

4.4.3.2 Influence of "Exposure to sunlight."

Exposure is an important parameter that affects the growth of the species in time and the percentage of species that will reach death in the entire lifetime project. The project data was obtained using exposure to sunlight of "full sun"; so, keeping the other parameters such as "tree condition" and " tree mortality rate" unchanged and using "partial sun" and "full sun" conditions (Table 4-16):

TYPE	full sun [kg/10 years]	partial sun [kg/10 years]	full shade [kg/10 years]
N1	0,208	0,184	0,153
N2	0,439	0,389	0,322
N3	0,158	0,140	0,117
N4	0,513	0,454	0,377
P-1	0,099	0,088	0,073
P-2	0,192	0,170	0,141
P-3	0,369	0,326	0,272
P-5	0,156	0,138	0,116
P-6	0,208	0,185	0,155
P-7	0,208	0,185	0,153
I-1	0,510	0,451	0,155
I-2	0,535	0,474	0,393
FT-1	0,510	0,474	0,393
FT-2	0,330	0,451	0,374
E-1	0,297	0,292	0,241

Table 4-16 $PM_{2.5}$ removed for each sector and each type, in different exposure conditions to sunlight.

This data is multiplied for the number of interventions for each type in each sector reported in (Table 4-8). , the results are reported in Table 4-17.

Sector	PM 2.5 removed in fist ten years_full sun [kg/10 years]	PM 2.5 removed in fist ten years_partial sun [kg/10 years]	PM 2.5 removed in fist ten years_full shade [kg/10 years]
1	796	473	373
2	1159	702	545
3	1035	482	492
4	804	715	377
5	1309	776	615
6	791	488	379
7	628	357	292
Total [kg/10 years]	**6522**	**3993**	**3074**
Δ[%]	-	-39%	-53%

Table 4-17 $PM_{2.5}$ removed for each sector for the tree exposure to sunlight condition, in the last two rows total removal with a different configuration, and percentage variation respect the first value.

The results of are illustrated in Figure 4-9.

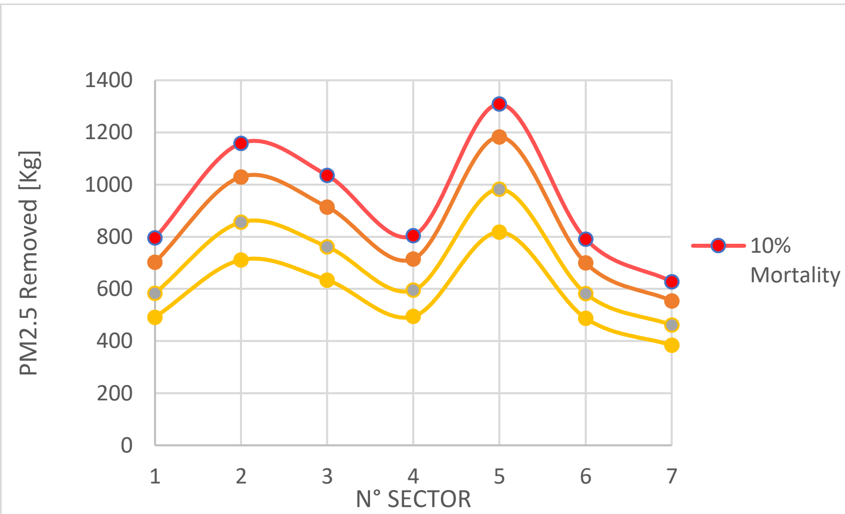


Figure 4-9 Capture performance of each sector for three different exposures to sunlight condition

4.4.3.3 Influence of "Tree condition."

"Tree condition", or the state of health of the plant species, at the time of planting has a substantial impact on its growth and consequently on the ability to remove $PM_{2.}$ over time. The conditions of the project are "full sun" and "excellent tree condition", which are the best possible conditions for getting the highest result in terms of removal of the particulate matter itself. In this case, we want to evaluate the results that we obtain by changing the tree condition parameter and keeping the other parameter unchanged. The results are shown in Table 4-18.

TYPE	$PM_{2,5}$ REMOVED_exc. [kg/10 years]	$PM_{2,5}$ REMOVED_good [kg/10 years]	$PM_{2,5}$ REMOVED_poor[kg/10 years]
N1	0,208	0,184	0,153
N2	0,439	0,389	0,322
N3	0,158	0,140	0,117
N4	0,513	0,454	0,377
P-1	0,099	0,088	0,073
P-2	0,192	0,170	0,141
P-3	0,369	0,326	0,272
P-5	0,156	0,138	0,116
P-6	0,208	0,185	0,155
P-7	0,208	0,185	0,153
I-1	0,510	0,451	0,155
I-2	0,535	0,474	0,393
FT-1	0,510	0,474	0,393
FT-2	0,330	0,451	0,374
E-1	0,297	0,292	0,241

Table 4-18 $PM_{2.5}$ removed for each sector and each type, in different tree conditions.

This data is multiplied for the number of interventions for each type in each sector reported in (Table 4-8). , the results are reported Table 4-19.

Sector	$PM_{2,5}$ REMOVED_exc. [kg/10 years]	$PM_{2,5}$ REMOVED_good [kg/10 years]	$PM_{2,5}$ REMOVED_poor[kg/10 years]
1	796	717	320
2	1159	1050	467
3	1035	940	423
4	804	730	326
5	1309	1186	529
6	791	718	323
7	628	569	253
Total [kg/10 years]	**6522**	**5910**	**2641**
Δ[%]	-	-9%	-60%

Table 4-19 $PM_{2.5}$ removed for each sector for three tree conditions, in the last two rows total removal with a different configuration, and percentage variation respect the first value.

The results of Table 4-20 are illustrated in Figure 4-10.

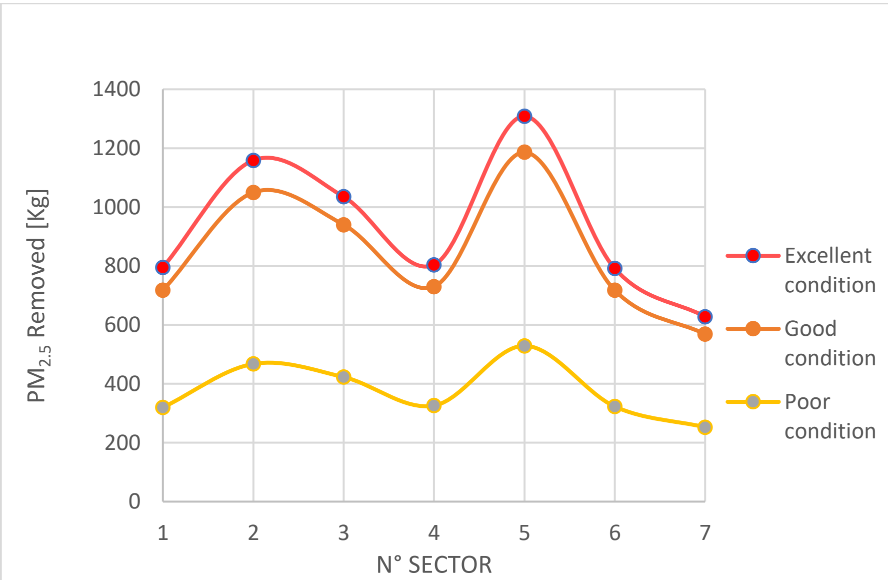


Figure 4-10 Capture performance of each sector for three different tree conditions

4.4.3.4 "Ready to go species" in all the interventions.

As described in paragraph (0), among the different species used, there are trees of the first magnitude, such as (*Quercus robur*, *Fraxinus excelsior, Populus alba, Salix),* which are planted with a diameter of 4 cm. There are, however, some types of intervention (P3, P5;P6, P7) that provide for the planting of species with immediate effect, that as they are larger, they can immediately explain the objectives for which they have been positioned as the shading of the infrastructure in the case of P7 of historical channels requalification in the case of P5. Ready to go species, unlike the first-size trees, have an initial diameter of 8 cm, with a consequent more remarkable ability to remove the initial particulates than those of the first size. In this paragraph, it was intended to assess the increase in the capacity of the species to remove particulate if all types of plants planned in work were adopted in the four species with immediate effect instead of the first magnitude.

The results are shown in (Table 4-20)

TYPE OF INTERVENTION	$PM_{2,5}$ REMOVED [kg/10 years]	$PM_{2,5}$ REMOVED Introducing "ready to go species" [kg/10 years]
N1	0,208	0,208
N2	0,439	0,504
N3	0,158	0,158
N4	0,513	0,599
P-1	0,099	0,099
P-2	0,192	0,215
P-3	0,369	0,369
P-5	0,156	0,156
P-6	0,208	0,208
P-7	0,208	0,208
I-1	0,510	0,551
I-2	0,535	0,535
FT-1	0,510	0,551
FT-2	0,330	0,330
E-1	0,297	0,321

Table 4-20 PM2.5 removed for each sector and for each type, project configuration and ready to go species.

This data is multiplied for the number of interventions for each type in each sector reported in (Table 4-8). , the results are reported in Table 4-21.

Sector	PM2,5 REMOVED_exc. [kg/10 years]	PM2,5 REMOVED ready to go species [kg/10 years]
1	796	841
2	1159	1198
3	1035	1070
4	804	829
5	1309	1389
6	791	819
7	628	646
Total [kg/10 years]	6522	6792
Δ[%]	-	4%

Table 4-21 PM2.5 removed each sector by substituting the first size tree with "ready to go species".

The results of Table 4-21 are illustrated in Figure 4-11.

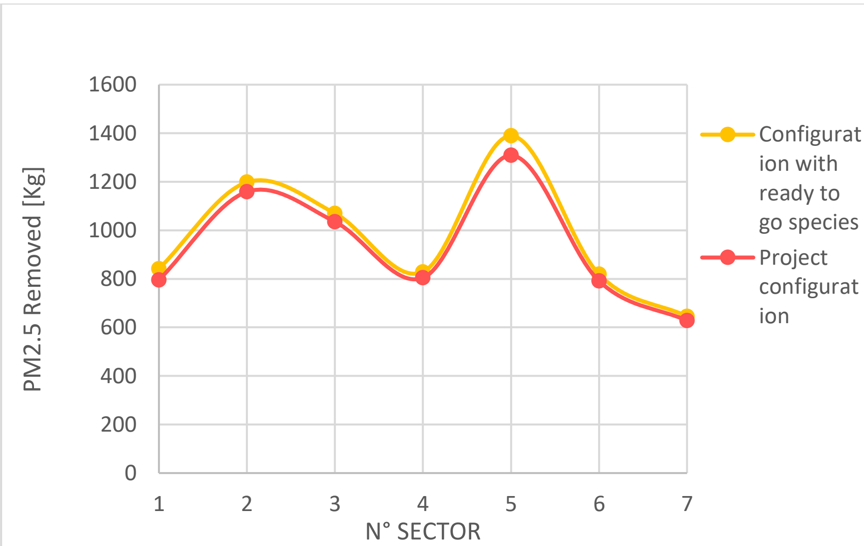


Figure 4-11 Capture performance of each sector for the staring configuration by using ready to go species.

Highway Sector		Emissions PM2.5 [kg/year]	Capture PM2.5 [kg/year]	Capture[%]	Capture PM2.5 kg/year with ready to go species	Capture with ready to go species [%]
1	Autostation Reggiolo-Rolo - Junction A22	4633,7	79,6	-1,7%	97,1	-2,10%
2	From Junction A22 (excluded) to exit S.Possidonio-Concordia-Mirandola (escluso)	7494,8	115,9	-1,5%	130,5	-1,70%
3	From exit S. Possidonio-Concordia-Mirandola to exit S.Felice s/P-Finale Emilia (excluded)	9398,2	103,5	-1,1%	115,6	-1,20%
4	From exit S.Felice s/P-Finale Emilia to Exit of Cento (excluded)	8325,1	80,4	-1,0%	93,5	-1,10%
5	From Exit of Cento to exit Poggio Renatico (excluded)	7038,5	130,9	-1,9%	170,8	-2,40%
6	From exit of Poggio Renatico to Junction A13 (excluded)	7639,8	79,1	-1,0%	97,2	-1,30%
7	From junction of A13 to exit Ferrara Sud	3873,7	62,8	-1,6%	71,8	-1,90%
	TOTAL BALANCE	**48403,8**	**652,2**	**-1,3%**	**776,6**	**-1,6%**

Table 4-22 Overall balance $PM_{2.5}$(Infrastructure emissions-capture green operas with the configuration that has them ready to go species

4.4.3.5 Variation (Changing some species)

Remembering that the species outside of the interventions I1 and I2 have not been chosen following criteria of environmental mitigation; It has been selected to replace an arboreal species and, at most, a shrubby species in that planting scheme that bring trees low absorption potential. In this section, we want to observe the result obtained by replacing one tree and one shrub (Pero selvatico, and Pallon di Maggio) with other three different trees/shrubs (Carpino, Frassino ossofilo, Ligustro): The planting scheme on which it was considered to make the changes required are the following:

- N2 Tree-shrub hedge with ecological reconnection function
- N3 Multi-specific shrub
- N4 Plurispecific forest
- P3 Interventions of ornamental type
- FT2 Transverse buffer strips for water quality restoration

Previous (common name)	Previous species	Previous_I-Tree species	New (common name)	New species	New_I-Tree species	$PM_{2.5}$ removed_old species[kg/10 years]	$PM_{2.5}$ removed_new species[kg/10 years]	Implant Typology
Pero selvatico	*Pyrus Pyraster*	*Pyrus species*	Carpino	*Carpinus betulus*	*Carpinus betulus*	13	26	N2
Pero selvatico	*Pyrus Pyraster*	*Pyrus species*	Frassino ossofilo	*Fraxinus oxycarpa*	*Fraxinus oxycarpa*	13	22	N3
Pero selvatico	*Pyrus Pyraster*	*Pyrus species*	Carpino	*Carpinus betulus*	*Carpinus betulus*	13	26	N4
Pallon di Maggio	*Viburnus opulis*	*Viburnus species*	Ligustro	*Ligustrum vulgare*	*Ligustrum species*	8	15	P3; FT-2

Table 4-23 New tree/shrub that substitutes "Pero selvatico" and "Pallon di Maggio".

TYPE	$PM_{2,5}$ REMOVED [kg/10 years]	$PM_{2,5}$ REMOVED Introducing 3 efficient species [kg/10 years]
N1	0,208	0,208
N2	0,439	0,452
N3	0,158	0,167
N4	0,513	0,526
P-1	0,099	0,099
P-2	0,192	0,192
P-3	0,369	0,440
P-5	0,156	0,156
P-6	0,208	0,208
P-7	0,208	0,208
I-1	0,510	0,510
I-2	0,535	0,535
FT-1	0,510	0,510
FT-2	0,330	0,337
E-1	0,297	0,297

Table 4-24 $PM_{2.5}$ removed each sector for initial configuration and configuration obtained by substituting three species with three more efficient species.

This data is multiplied for the number of interventions for each type in each sector reported in (Table 4-8). , the results are reported in Table 4-25.

Sector	$PM_{2,5}$ REMOVED_exc. [kg/10 years]	$PM_{2,5}$ REMOVED Introducing 3 efficient species [kg/10 years]
1	796	809
2	1159	1175
3	1035	1049
4	804	812
5	1309	1321
6	791	820
7	628	638
Total [kg/10 years]	**6522**	**6624**
Δ[%]	-	2%

Table 4-25 PM2.5 removed for each sector for two different configurations, the starting project and a solution obtained by using three species more efficient.; in the last two rows, total removal with different configuration and percentage variation respect the first value.

The results of Table 4-25 are illustrated in Figure 4-12

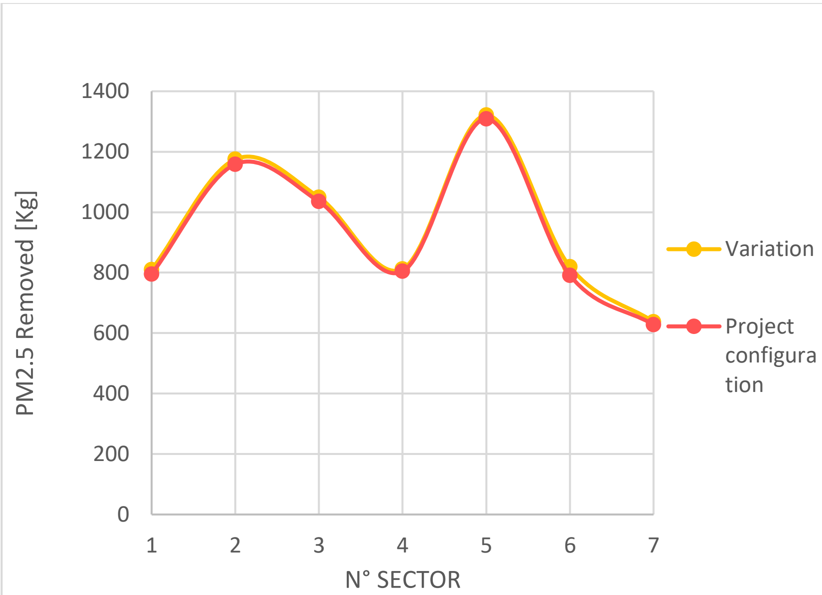


Figure 4-12 Capture the performance of each sector for the two configurations, the initial l and that obtained by introducing three species more efficient.

4.4.3.6 Considering the 5 More utilized species with 100% mortality

Not all species presents have the same weight on the overall dust capture balance. Some species are more frequent. Moreover, have a higher removal potential. We want to estimate the incidence of the total result if these species had a 100% mortality rate. This species, with its potential capture value, is reported in Table 4-26.

Common name	Italian species	I-Tree species	First year capture potential_10% mor [g]	Ten years capture potential_10% mort [g]	Ten years capture potential_100% mort [g]
Fusaggine	Euonymous eropeus	Euonymus species	0,5	9,5	5,5
Prugnolo	Prunus spinosa	Prunus shrubs species	0,2	12	4,2
Ligustro	Ligustrum vulgare	Ligustrum species	0,3	15	8,6
Rosa Canina	Rosa canina	Asimina triloba	0,3	10	5,8
Sanguinello	Cornus sanguinea	Cornus species	0,1	8	4,2

Table 4-26 Capture potential for the most used species, with their value calculated in 10% mortality and 100% mortality.

The result for each sector is reported in Table 4-27.

TYPE OF INTERVENTION	$PM_{2,5}$ REMOVED [kg/10 years]	$PM_{2,5}$ REMOVED with 5 species 100% mortality [kg/10 years]
N1	0,208	0,222
N2	0,439	0,308
N3	0,158	0,115
N4	0,513	0,442
P-1	0,099	0,059
P-2	0,192	0,357
P-3	0,369	0,222
P-5	0,156	0,156
P-6	0,208	0,208
P-7	0,208	0,208
I-1	0,597	0,510
I-2	0,535	0,357
FT-1	0,510	0,510
FT-2	0,330	0,263
E-1	0,297	0,231

Table 4-27 $PM_{2.5}$ removed each sector for each type, with initial configurations with all species at 10% mortality and the second configuration with five more used species with 100% mortality.

This data is multiplied for the number of interventions for each type in each sector reported in (Table 4-8). , the results are reported in Table 4-28..

Sector	$PM_{2,5}$ REMOVED_exc. [kg/10 years]	$PM_{2,5}$ REMOVED with 5 species 100% mortality [kg/10 years]
1	796	660
2	1159	867
3	1035	715
4	804	542
5	1309	944
6	791	561
7	628	453
Total [kg/10 years]	**6522**	**4742**
Δ[%]	-	-27%

Table 4-28 PM2.5 removed for the two different configurations, in the first column the original with all the species with 10% mortality, in the second column with the five more essential species with 100% mortality. In the last two rows, total removal with a different configuration and percentage variation respect the first value.

The results are illustrated in Figure 4-13.

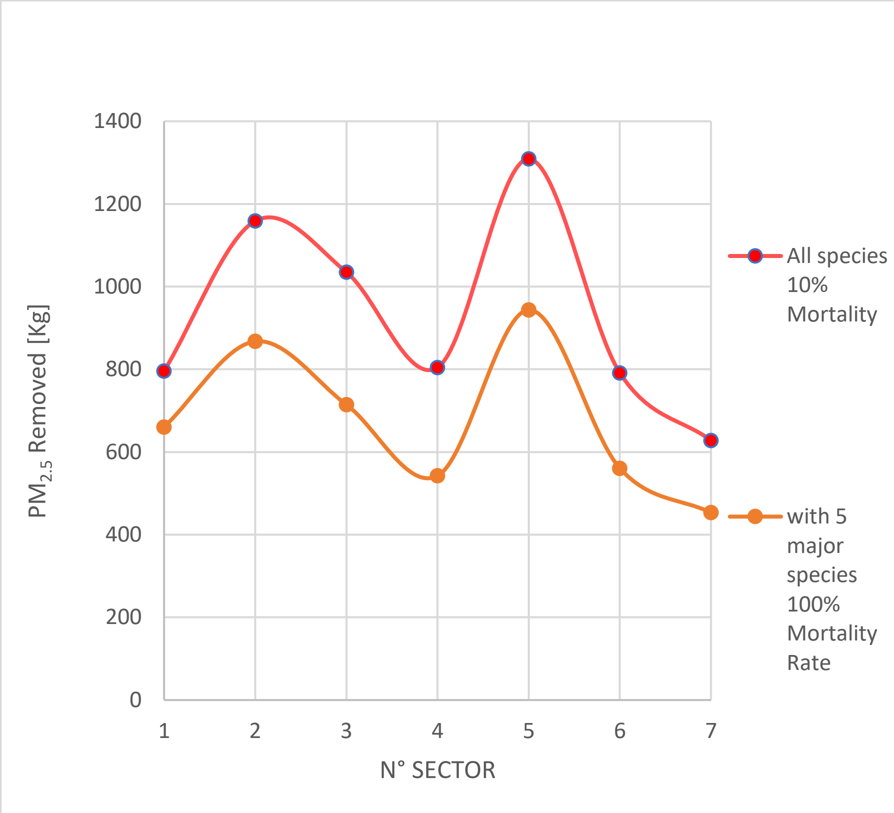


Figure 4-13 PM2.5 removed for each sector with initial configurations with all species at 10% mortality and with the second configuration with five more used species with 100% mortality.

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4.5 Discussion

The analysis of $PM_{2.5}$ emissions from the infrastructure gave a starting point that provided a value for comparison with particles removed from the vegetation. Results obtained on the amount of $PM_{2.5}$ removed from interventions designed explicitly for atmospheric mitigation, such as “I1” and “I2”, justify the interventions themselves. They demonstrate effectiveness managing to reduce 0.2%, with a tip of 1.0% in the first section where there are 60% (between I1 and I2) of all the interventions provided. As shown in the table(Table 4-13), the amount of dust removed considering all planned green interventions is 1.3 % of that emitted by the infrastructure, with peaks of 1.9% and 1.7% respectively in the fifth and seventh sectors. The average annual catch potential is helpful for comparison but at the same time has no physical evidence, as the purification capacity of green interventions is directly related to their growth and is therefore minimal in the first year and increasing with time.

In paragraph 4.4.3, the results obtained by varying the basic parameters of the I-Tree Planting Calculator have been reported. By evaluating Table (Table 4-15), in case the mortality rises from 10 to 30%, a reduction of 11% of particulate capture was observed, which drops to 29% and 52% in case of a mortality rate of 90%. It is essential to underline that if there will be the death of almost all the species over ten years, it will get an overall reduction of more than half of the total catch capacity.

If the project conditions are unchanged, it can be seen by looking at the data in Table(Table 4-16). As moving from a situation” full sun” to a “partial sun” condition, there is a reduction of 11% of the total capacity to reduce the dust emitted and that further decreases by 59% in the state “full shade”. From these results, it is clear how much to affect the outcome is the transition from partial sun condition to “full shade“, as has been assumed. The project time is ten years, but the species are expected to stay in place for several decades. Considering that the parameter dramatically affects the growth of plant species is easily guessed as it is a variable that has a significant incidence.

Just as exposure to sunlight affects growth, tree condition at the time of planting is an essential parameter for growth itself. Passing from the excellent condition to the good condition has an ulterior decrease of 66% regarding the initial value as reported in Table 4-17 . This shows how important it is to choose species in the best possible states at implementation.

There are some types of interventions (P5, P6, P7) that have a “ready to go species”, applying this type of species also for other kinds of intervention, the results in the table are obtained. The use of the species leads to an overall increase of 4% in dust capture capacity with peaks of 6% in the first and fifth sectors. As was expected, the use of the “ready to go species” leads to a total benefit in removing dust.

A scenario has been created in which there is an increase in the benefit of green interventions. Two species have been replaced with as many species that have a higher particle capture capacity. In the results in the tables(Table 4-25), it is noted that the increase in dust removal by adding all sectors is equal to 2%. It should be remembered that the replaced species were chosen without the aim of mitigating pollution. Therefore, it is necessary to assess whether the new species maintain the initial objectives (shadowing, masking infrastructure, etc.).

Paragraph 4.4.3.6 was analysed a scenario in which the five most impactful species in dust removal have a 100% mortality. As shown in the graph (Figure 4-13) and the data in the table (Table 4-28), there is an overall decrease of 27% of the overall capacity to remove particulates. This result shows us how important it is to have a wide variety of species with a high capture capacity of $PM_{2.5}$ so as not to have problems in the plant's overall efficiency if one of these species should die along with the duration of the plant project.

Therefore, it can be concluded that green interventions lead to a significant environmental benefit, which is one of the instruments which, in a comprehensive system of interventions acting on different fronts (reduction of emissions at source, relocation of emission sources concerning population, etc..). Can correctly effectively to the correct environmental integration of the work. The additional compensatory contribution resulting from mitigation actions with function is essential naturalistic, landscaped, ecological and agro-environmental, allowing to reach absorption values not negligible. It is important to note that the amount of dust captured by vegetation has been calculated using the background concentration of $PM_{2.5}$. Still, the vegetation's attention is more significant because it is close to the infrastructure. As given in the above paragraph 3.5.2, the amount of dust removed is directly proportional to the concentration of $PM_{2.5.}$ Therefore, the calculated value is underestimated compared to the actual computed value.

It is also important to underline that the 10-year period on which the outcome analyses were based emissive does not correspond to the entire period of the exercise of the opera. The naturalistic mitigations themselves will contribute to the improvement of air quality for a much more extended period. The hypothesis of more scenarios far in time, however, it is difficult to apply in this historical moment of “passage” in which level policy are outlining clear emission reduction targets that can only be reached with guidelines now defined and shared at the international level and in the scientific community but which, now have not been still translated into actual practical actions or feedback. An example of all is the penetration of electric vehicles in the car park future, strongly promoted to programme level because it directly relates to a significant reduction in vehicular emissions.

It is still tough to estimate the impact on the short-medium and long term. It is, however, plausible to imagine that the natural, technological advance and the implantation proposed at the policy level will lead to a steady reduction in traffic emissions. In this case, the annual emissions of $PM_{2.5}$ will be reduced more and more as of time. Consequently, the absorption of green, which will remain constant for long periods once reached maturity, will significantly impact the total issued.

5 CONCLUSION

This work has highlighted how the Dry deposition of $PM_{2.5}$ on vegetation is a complex phenomenon influenced by many factors. However, it has provided valid indications to understand the phenomenon better and create a plant system that allows having a high removal capacity of $PM_{2.5.}$ Demonstrating that planting vegetation to mitigate high concentrations of $PM_{2.5}$ is an effective solution. The species it prefers are the evergreen conifers that allow having a more remarkable ability to catch particles during the whole solar year and maintain the crown during the winter season (critical for high concentrations of $PM_{2.5}$), unlike deciduous species. The shape of the needle-shaped leaves and wax on its surface allow it to have greater efficiency. If it is maintained in a good state, the effectiveness of the plants increases with increasing time, thanks to the growth of plant species.

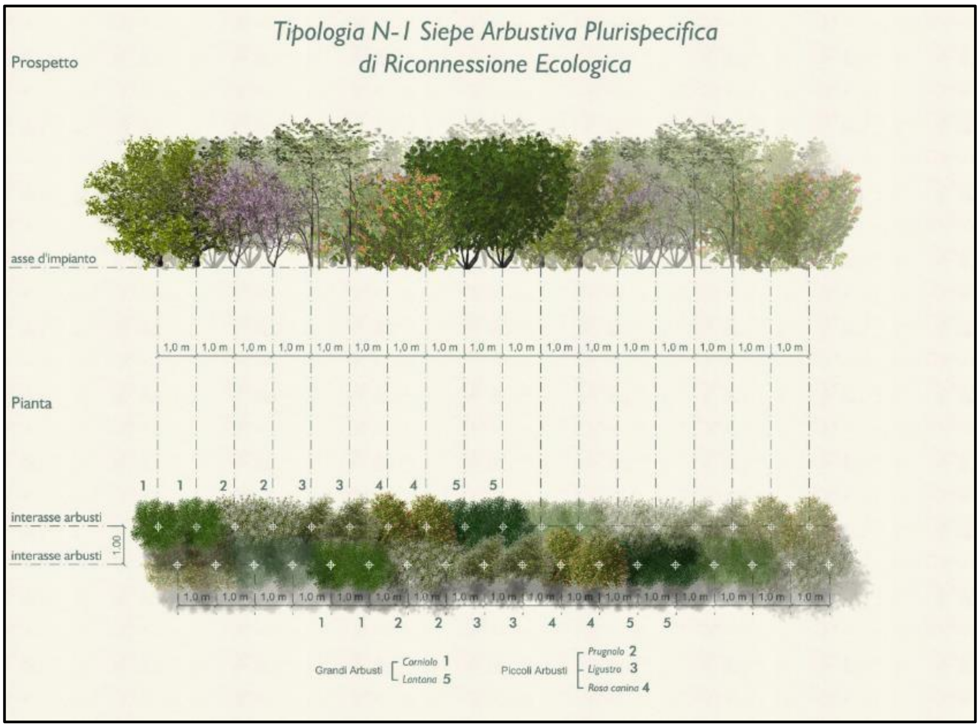
The case study allowed us to give an order of magnitude of pollutant removals caused by the various green interventions planned along the route. The 1.3% of the dust emitted is trapped, with peaks of 1.9% and 1.7% in the fifth and the seventh sectors. These values represent a default estimate for two reasons: The removal is calculated based on the environmental concentration that occurs in Wichita (USA), which is equal to 20 $\mu g/m^{3,}$ slightly lower than the background concentration that occurs in the areas crossed by the highway (22 $\mu g/m^3$). The second reason lies in the fact that the background concentration is lower than that present where vegetation is because of the emissions produced by vehicles in transit. Therefore, it is essential to highlight that the capacity of vegetation to remove particulates grows with time while the amount of dust emitted is expected to decrease due to the decrease in vehicle emissions and the introduction of cars into the vehicle of vehicles in the vehicle park.

These considerations, therefore, confirm the benefits produced by this type of intervention. The dispersion of pollutants and the variation in fluid dynamics caused by the presence of the vegetation it is not considered. The usable plant species are only those related to US habitats and climates. Future developments of i-Tree will have to expand the plant species present in the database. They will have to consider the phenomenon of dispersion without this goes at the expense of the model usability.

6 APPENDIX

INTERVENTION TYPE N1

Dimension: 9 m

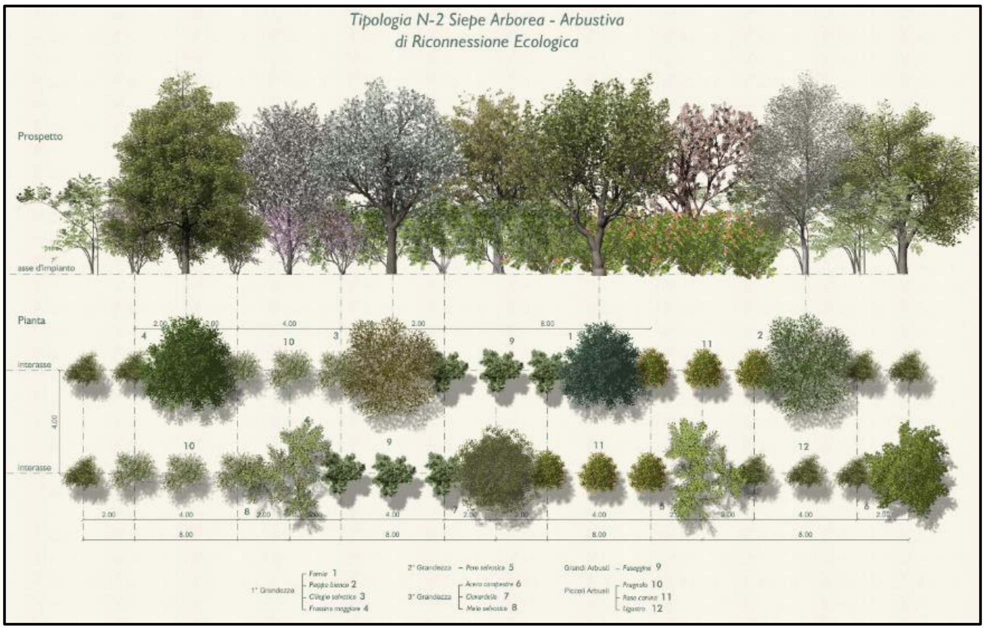


Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Corniolo	4				
Prugnolo	4				
Ligustro	4				
Rosa Canina	4				
Lantana	4				

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.208	**0.007**

Figure 6-1 Intervention type N1

INTERVENTION TYPE N2	Dimension: 128 m²

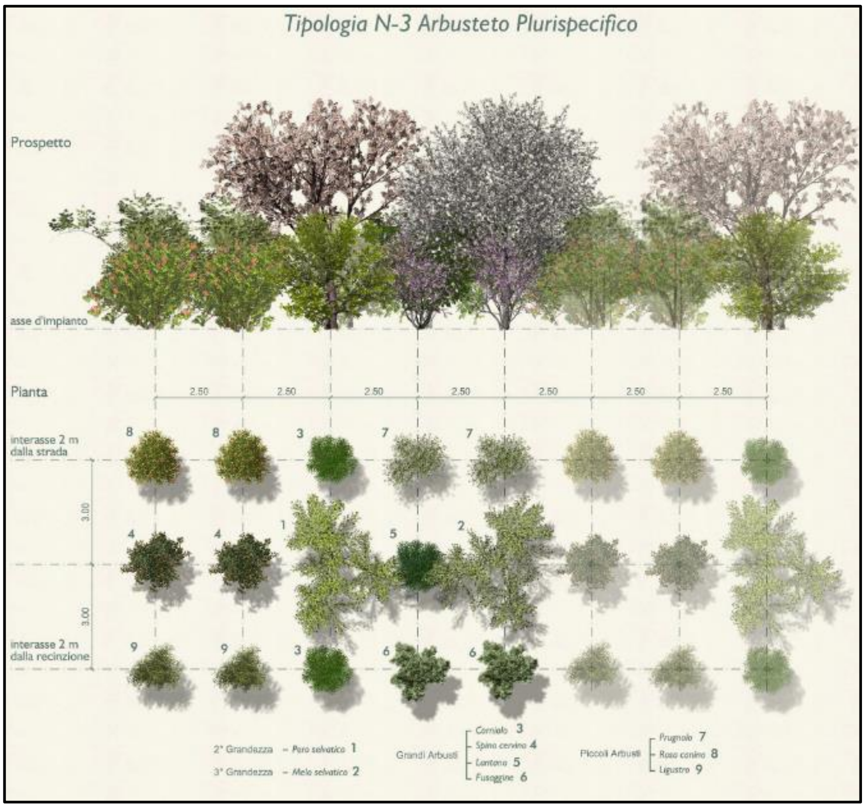


Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Farnia	1	Acero Campestre	1	Rosa Canina	6
Pioppo Bianco	1	Ciaverdello	1	Ligustro	6
Ciliegio Selvatico	1	Melo Selvatico	1		
Frassino Maggiore	1	Fusaggine	6		
Pero Selvatico	1	Prugnolo	6		

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.439	**0.012**

Figure 6-2 Intervention type N2

INTERVENTION TYPE N3	Dimension: 60 m²

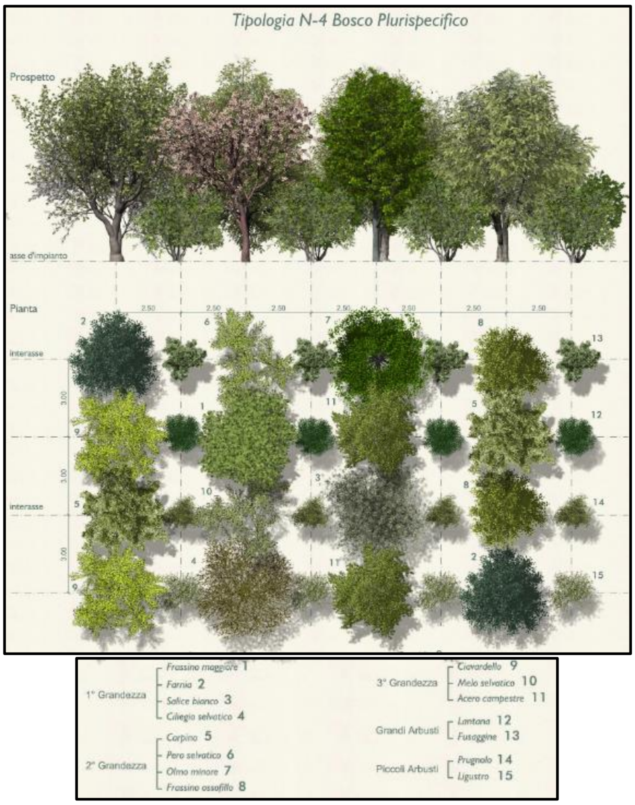


Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Pero Selvatico	1	Fusaggine	2		
Melo Selvatico	1	Prugnolo	2		
Corniolo	2	Rosa Canina	2		
Spino Cervino	2	Ligustro	2		
Lantana	1				

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.158	**0.006**

Figure 6-3 Interveniton type N3

INTERVENTION TYPE N4	Dimension: 157.5 m²

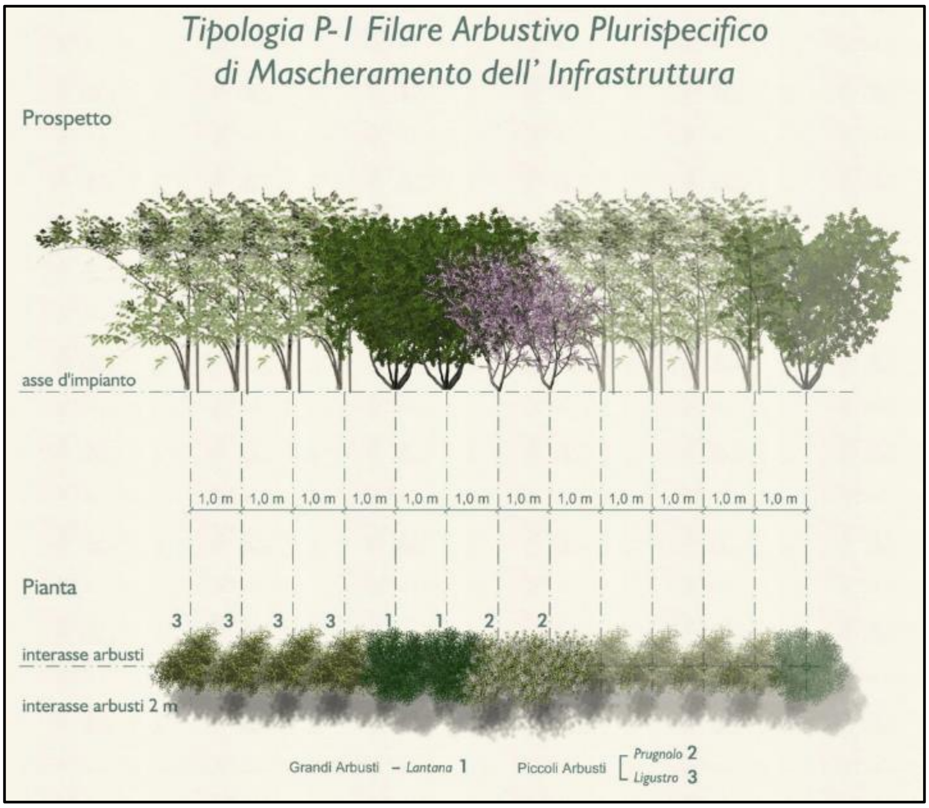


Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Frassino Maggiore	1	Pero Selvatico	1	Acero Campestre	2
Farnia	2	Olmo Minore	1	Lantana	4
Salice Bianco	1	Frassino Ossofillo	2	Fusaggine	4
Ciliegio Selvatico	1	Ciaverdello	2	Prugnolo	4
Carpino	2	Melo Selvatico	1	Ligustro	4

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.513	**0.015**

Figure 6-4 Intervention type N4

INTERVENTION TYPE P-1	Dimension: 7 m

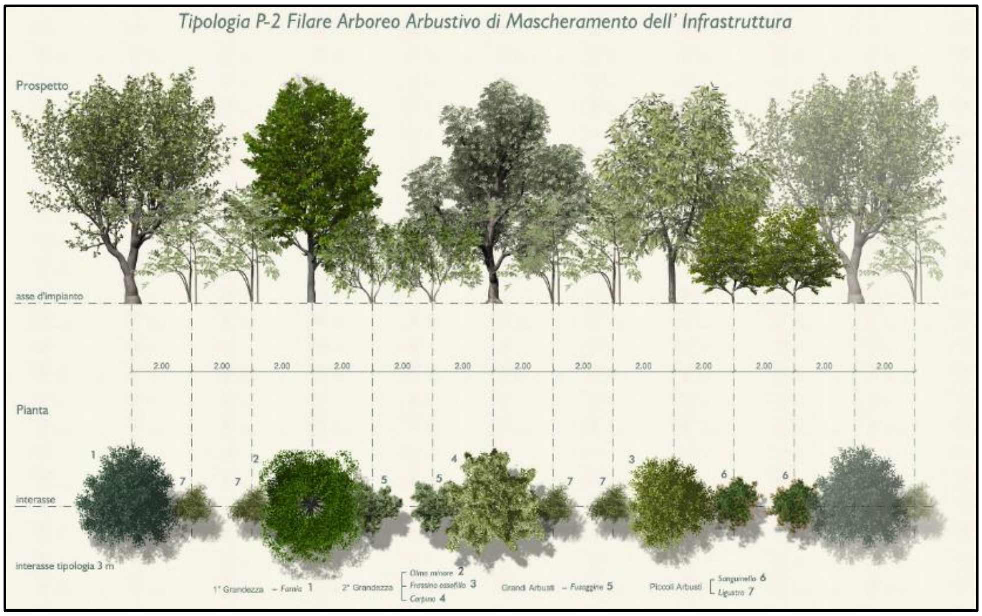


Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Lantana	2				
Prugnolo	2				
Ligustro	4				

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.099	**0.003**

Figure 6-5 Intervention Type P1

INTERVENTION TYPE P-2	Dimension: 22 m

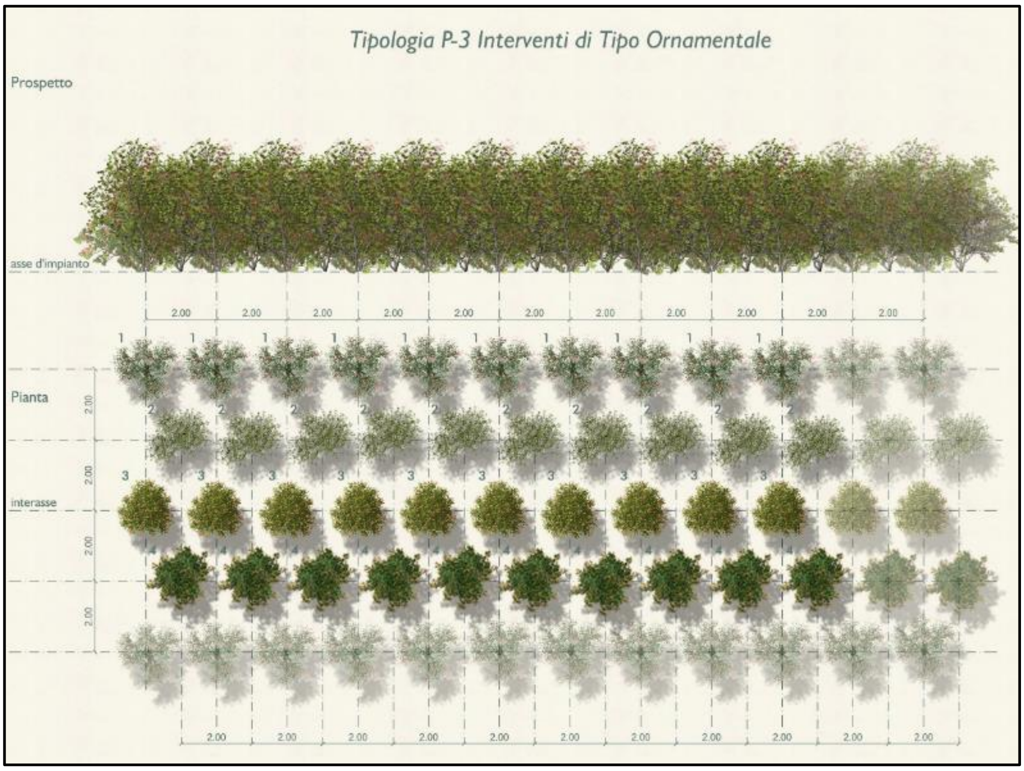


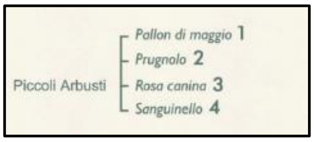
Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Farnia	1	Sanguinello	2		
Olmo Minore	1	Ligustro	4		
Frassino Ossofillo	1				
Carpino	1				
Fusaggine	2				

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.192	**0.005**

Figure 6-6 Intervention type P2

INTERVENTION TYPE P-3	Dimension: 114 m²



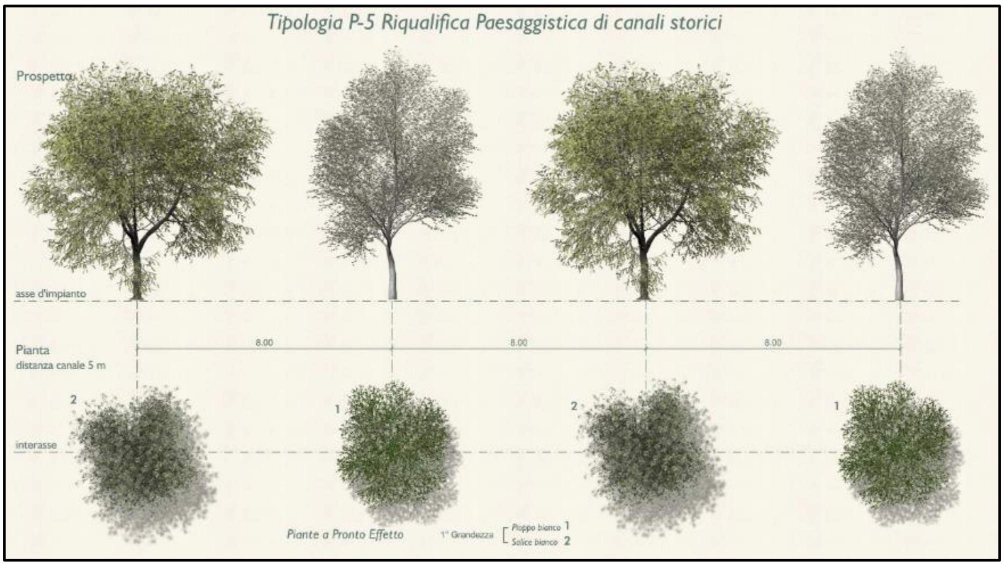


Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Pallon di Maggio	10				
Prugnolo	10				
Rosa Canina	10				
Sanguinello	10				

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.369	**0.009**

Figure 6-7 Intervention type P3

INTERVENTION TYPE P-5	Dimension: 24 m

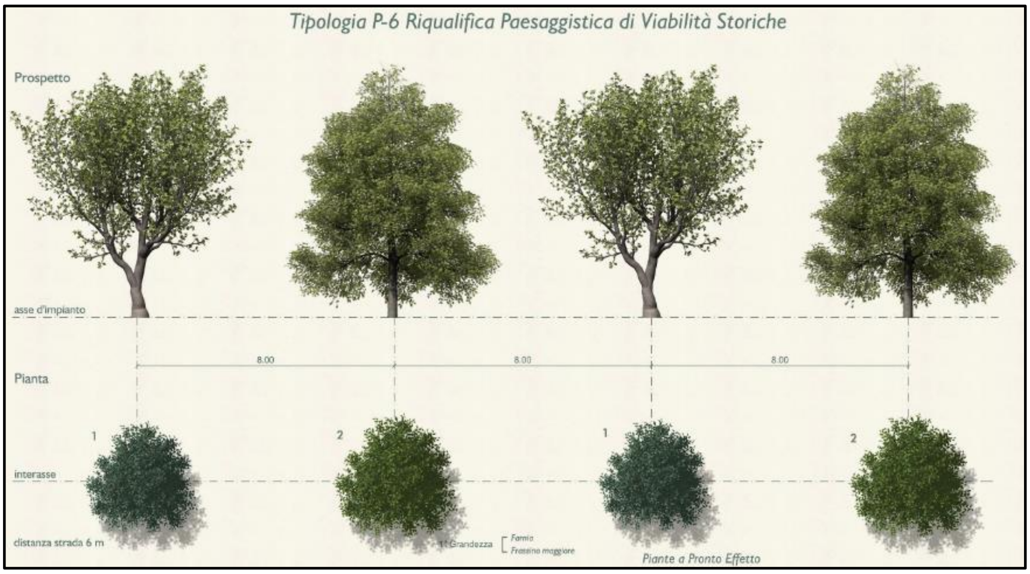


Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Pioppo Bianco - circ. 25 cm Ø 8 cm	2				
Salice Bianco - circ. 25 cm Ø 8 cm	2				

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.156	**0.005**

Figure 6-8 Intervention type P5

INTERVENTION TYPE P-6	Dimension: 24 m

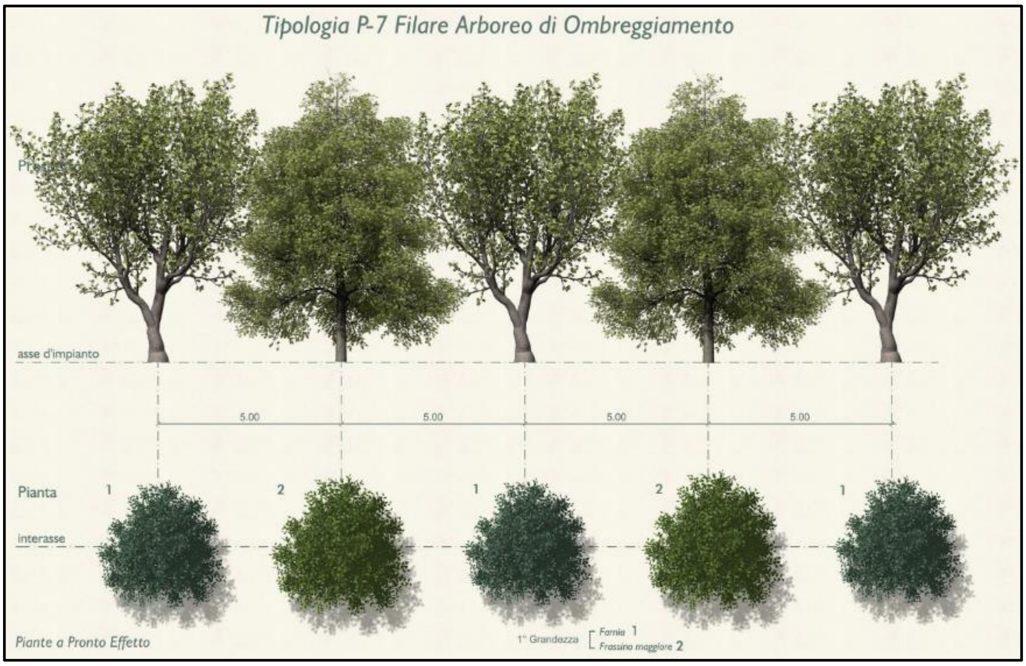


Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Farnia circ. 25 cm Ø 8 cm	2				
Frassino Maggiore circ. 25 cm Ø 8 cm	2				

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.208	**0.007**

Figure 6-9 Intervention type P6

# INTERVENTION TYPE P-7	**Dimension: 20 m**

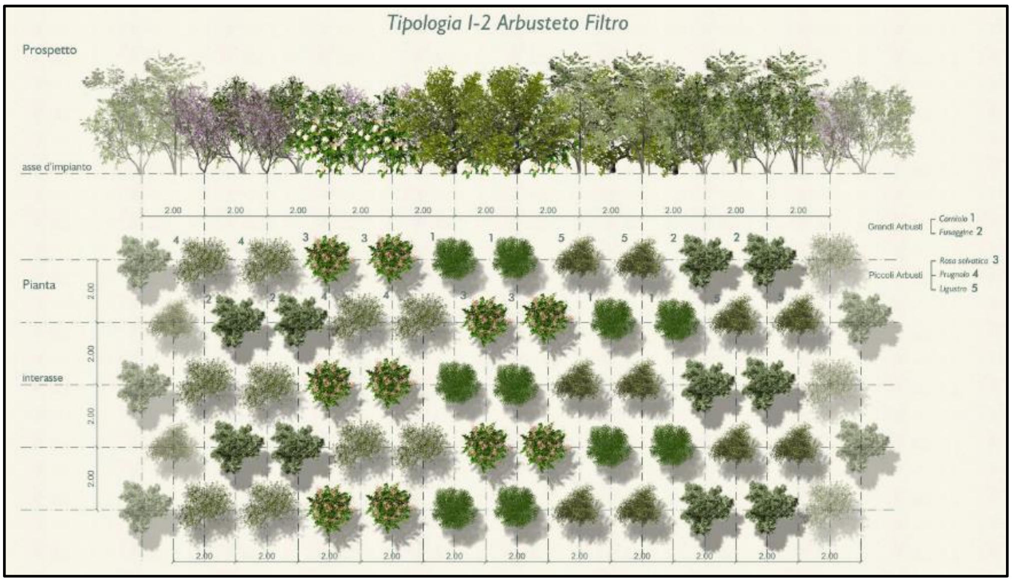


Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Farnia circ. 25 cm Ø 8 cm	2				
Frassino Maggiore circ. 25 cm Ø 8 cm	2				

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.208	**0.007**

Figure 6-10 Intervention typ P7

INTERVENTION TYPE FT-1			Dimension: 34.5 m²		



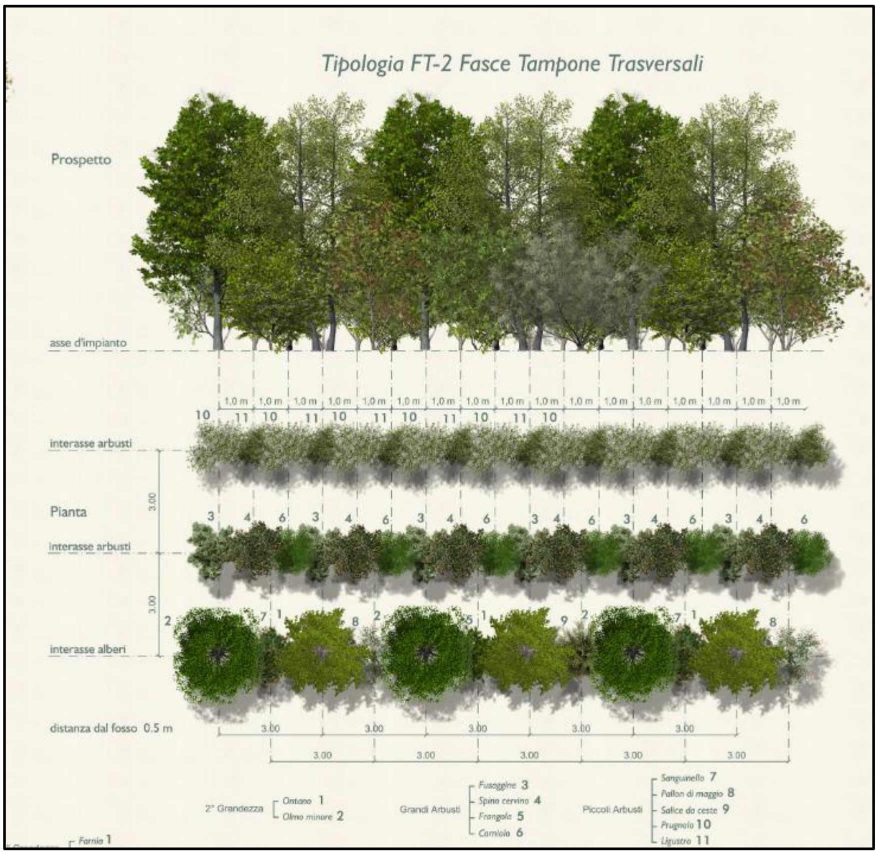
Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Farnia	1	Frassino Ossofillo	5		
Salice Bianco	1	Acero Campestre	3		
Pioppo Nero	4	Ciaverdello	3		
Carpino Bianco	4				
Olmo Minore	5				

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.510	**0.012**

Figure 6-11 Intervention type FT-1

INTERVENTION TYPE FT-2

Dimension: 63 m²



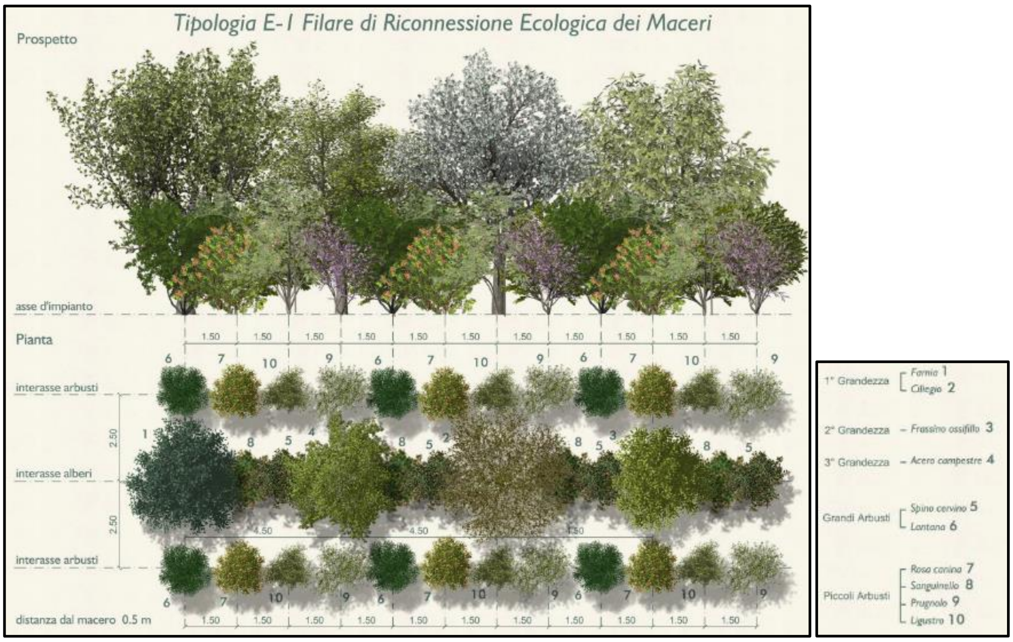
Composition					
Specie	**N.**	**Specie**	**N.**	**Specie**	**N.**
Ontano	2	Corniolo	4		
Olmo Minore	2	Sanguinello	1		
Fusaggine	4	Pallon di Maggio	1		
Spino Cervino	4	Salice da ceste	1		
Frangola	1	Prugnolo	6		

Capture potential	
First ten years (kg/10 years)	**First-year (kg/year)**
0.330	**0.010**

Figure 6-12 Intervention type FT-2

INTERVENTION TYPE E-1

Dimension: 82.5 m²



Composition

Specie	N.	Specie	N.	Specie	N.
Farnia	1	Lantana	6		
Cigliegio	1	Rosa Canina	6		
Frassino Ossofillo	1	Sanguinello	4		
Acero Campestre	1	Prugnolo	6		
Spino Cervino	4	Ligustro	6		

Capture potential

First ten years (kg/10 years)	First-year (kg/year)
0.297	**0.009**

Figure 6-13 Intervention type E1

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