Urban forest effects on the accumulation of CO_2 in the atmosphere and vice versa: A review

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Abstract

Nowadays, humanity is facing various social problems such as climate change. One of the causes is pollution, as it favors the accumulation of greenhouse gasses. In recent years, several solutions have been proposed to prevent pollution, which mainly affects large cities. One of these solutions is to combat it with urban forests, which can help reduce the carbon footprint. The goal of my research is to conduct a literature review on the effects of urban forests on pollution and vice versa. The study consists of two parts. In the first part, I searched for studies that quantify CO_2 sequestration or CO and analyzed the factors that control the uptake of CO_2 and CO from the atmosphere in European cities. In the second part, I analyzed the effects of air pollutants on tree growth. There are two types of factors that control the sequestration of carbon from the air: those related to tree characteristics (e.g., species, tree size, growing season, whether the tree species is evergreen or deciduous) and those related to management (e.g., use of pesticides and fertilizers, planting strategies, area). Regarding the second part of the study, trees in cities seem to grow faster in the short term, due to higher carbon dioxide concentration, higher temperatures, and thus a longer growing season. In the long term, this leads to faster aging and death.

Keywords: urban forest, pollution removal, monoxide carbon or dioxide carbon, Europe, tree growth, dendrochronology, urban trees, and pollution.

1. Introduction

Urban forest refers to all the trees living in densely populated areas like streetways, parks, and private properties. As urban forests inhabit cities, they live under polluted conditioning. However, urban forests and pollution affect each other. Urban forests bring benefits to the cities, for instance, saving energy, adaptation to climate, strengthening community resilience, reducing noise pollution, and purifying the urban water cycle. Overall one of the main benefits of trees for cities is the reduction of air pollution, especially CO and CO2. Instead, air pollution can affect the vitality of the urban forest.

Urban forests impact energy demand for cooling and heating buildings and reduce cooling energy costs (Safford et al., 2013)**.** The shade provided by trees lowers temperatures in the cities. Therefore, a large forested area in the city can reduce the energy consumption of air conditioning systems, especially in summer. In winter, trees help reduce energy consumption for heating homes, reducing wind speed. Furthermore, cities can change the climate and weather. For instance, in Barcelona, wind and solar radiation can be 10-30% and 20% lower, respectively, in the city center than in the periphery, while the temperature in the city center can be up to 8 ºC higher than in the surrounding area (Chaparro & Terrasdas, 2009). This last effect is called the heat island effect and is caused by high energy consumption and a large number of heat-absorbing areas (i.e. asphalt or cement can store solar radiation and release a lot of heat during the day). Later, this energy is converted into thermal energy, which is eventually radiated. In addition, urban forests allow cities to better adapt to climate change impacts, such as temperature fluctuations and extreme weather events (Safford et al., 2013). As noted earlier, cities are heat islands. Urban trees can not only help reduce this effect through their shade, but also reduce albedo and cooling evapotranspiration. Terrestrial albedo is the fraction of solar energy that the Earth returns to the stellar space without benefiting from that energy (Pelkowski, 2007).

In addition, urban forests help control storms and floods that could increase due to climate change. They intercept water through their canopies and reduce water accumulation in sewers. This prevents the risk of sewer overflows. Other benefits of urban trees include building community resilience, cleaning the urban water cycle, and reducing noise pollution. Cities with a bast urban forest tend to have more stable populations (Safford et al., 2013) as trees stimulate social interaction, have spiritual value, and provide residents with a sense of family and home. Urban forests help keep water in its natural cycle and limit pollution in waterways. This is is because trees filter water with their roots (Chaparro & Terrasdas, 2009). IIn cities, there is often a lot of asphalt or other materials that interfere with drainage and send rainwater directly to the sewage system. Calculations show that up to 90 % of rainwater can be lost because of this reason. In vegetated areas, only between 5 and 15 % is lost. Most cities around the world suffer from noise pollution from the activities of people in cities, such as construction, industry, and transport. In Barcelona, for example, there are some points where the noise exceeds 100 dB (Chaparro & Terrasdas, 2009), but the urban forest can reduce noise transmission.

Trees need carbon dioxide (CO_2) to photosynthesize and, thus, to survive. Therefore, trees in a polluted city can help reduce the concentration of CO_2 in the atmosphere because they store and capture it. The amount of CO_2 that trees in urban forests capture and store is quite variable, as reported in (Nowak et al., 2014). He conducted computer modeling of air pollution removal by trees in 55 US cities. The results showed that pollutant removal per unit canopy cover varied considerably from city to city, depending on pollutant concentrations, length of leaf season, amount of rainfall, and other meteorological variables. Compared to the U.S. and China, the number of studies in Europe analyzing the amount of air pollution removal by urban forests is smaller (Lin et al., 2019). However, to understand if urban forests can produce substantial benefits to the cities, a first step is to quantify the amount of pollution, especially CO_2 as is, by far, the greenhouse gas the most emitted into the atmosphere. Urban forests can help remove it from the atmosphere and the factors that constrain its removal can be identified.

High temperatures and CO_2 concentrations in the atmosphere can hasten trees' photosynthesis, and hence, tree growth. In the end, however, ends up having the contrary effect (Safford et al., 2013). Pollution and higher temperatures result in insufficient water and nutrients for the tree, causing stress, slower growth, and future development (Safford et al., 2013). Moreover, in the face of climate change, these negative effects may be exacerbated by a change in the water cycle, an increase in pathogens and pest activity, and physiological stress. Global warming is causing winter temperatures to rise, which is favorable for tree pests and pathogens because they have difficulties surviving at lower temperatures. Although some species may decline or become extinct, others may adapt better than their tree hosts because their very short lifespan allows them to adapt quickly. In addition, at higher temperatures, trees are more attractive to pests. This is because hot and dry environments increase carbohydrates concentration in tree foliage (Safford et al., 2013). Thus, both air pollution and climate change can affect tree development. While research on the benefits of urban forests to the cities is extensive, there is little research on the vitality and physiological status of urban forests. Understanding how pollution affects urban forests is critical because trees in urban forests can become an economic burden to cities due to the cost of removing dead specimens, accidents caused by fallen trees, and declines in ecosystem services provided by trees (Brandt et al., 2016).

The purpose of this systematic review is twofold. The first is to collect and analyze research that quantifies CO_2 and CO reduction by urban forests in European cities and to determine the factors that may alter CO_2 and CO sequestration. The second objective is to compile and synthesize the information contained in case studies on the effect of air pollutants on tree growth in urban forests.

2. Methodology

Urban forests anywhere in the world can consist of many different types of plants and trees, depending on factors such as climate. Similarly, pollution can be caused by many different processes and molecules such as CO_2, CH_4, NO_2, and other greenhouse gases but in this review, I focus on CO_2, and CO, as explained in the next section.

2.1. Search strategy

For both objectives, I searched in the ISI Web of the Knowledge database for a scientific article. Keyword searches were conducted using various combinations of relevant terms. For the first objective (i.e., studies quantifying CO_2 and CO reduction from urban forests in European cities), the following keywords were used: urban forest, pollution removal, carbon monoxide or carbon dioxide, and Europe. For the second objective (i.e., studies on the effect of CO_2 on tree growth in urban forests), a combination of the following keywords was used: tree growth, dendrochronology, urban trees, and pollution.

3. Urban forests and air pollution

3.1. Quantification of the removal of CO_2 by urban trees in European cities

Several studies have been conducted in Europe to determine whether urban trees can reduce CO_2 and CO concentration significantly in the atmosphere (Table 1). The articles analyzed here are from different cities and countries in Europe: Milan, Rome, Turin, Bristol, Strasbourg, London, and Lugo. Most studies quantify the removal of CO_2 using simulator software while others analyze their own measurements (Table1). Of the studies using simulator software, most used the i-Tree program to compare the effectiveness of CO_2 removal of different scenarios (Walters & Sinnett, 2021; Soares et al., 2011). The i-Tree is a suite of computer software tools developed through a collaborative public-private partnership. These tools are designed to assess and value the urban forest resource, understand forest risk, and develop sustainable forest management plans to improve environmental quality and human health (Nowak, 2020). Instead, the study developed by Fares et al., (2020) used AIRTREE to estimate the amount of CO_2, O_3, and PM sequestered by thousands of trees. AIRTREE is a one-dimensional multi-layer model, which couples soil, plant, and atmospheric processes and minimizes the energy balance throughout these compartments (Fares et al., 2020). Those studies not using simulators used their own methodology to estimate the carbon sequestration from the atmosphere in the scenarios analyzed (see Nicese et al., 2021; De la Sota et al., 2019).

The conditions of the urban forests that were analyzed in the different studies were different, and so was the result. The study area that captured the least amount of carbon dioxide is the Park of Valentino in Turin. The reason may be because of the dimensions of the park, its area is 42 ha. Most of the studies mention the number of trees living in the city where the study is computed but not the number of trees that are analyzed to make the study. The number of trees analyzed seems significant as the carbon sequestration is likely to be related to the characteristics of the trees in the urban forest. Those studies analyzing different scenarios using i-Tree such as the study computed in Bristol are interesting to understand, for instance, the increase of carbon sequestered by doubling the canopy area (Walters & Sinnett, 2021).

The variability in the amount of carbon sequestered among the case studies analyzed is likely related to the size of trees, the season and the month of the year, the green typology and its management, the land use and the management needed, the use of pesticides and fertilizers, the species of vegetation in the urban forest, the amount of wood, the planting strategies, etc. All these factors are discussed in the next section.

Table 1. Information about the city, the study area, the model, the species, the number of trees and the carbon sequestered by the trees of the study area of the studies analyzed in this part t

City	Study area	Model	Species	Number of trees	Carbon sequestered (ton / year)	Reference
Bristol	Bristol	i-Tree	*Fraxinus excelsior; Crataegus monogyna; Acer pseudoplatanus.*	NA	8425,97[1] 31218,75[2]	Walters & Sinnett, (2021)
Lisbon	Lisbon	i-Tree	*Celtis australis L.; Tilia L.;Jacaranda mimosifolia D.; Platanus L.;Acer negundo L.; Tipuana tipu (*Benth.*)* Kuntze; *Fraxinus angustifolia* Vahl.; *Lingustrum lucidum* Aiton fil.; *Koelreuteria paniculata* Laxm.; *Populus x canadensis* Moench; *Cercis siliquastrum* L.; *Populus nigra* L.; Other species	3033	1861	Soares et al., (2011)
Milan	Parco Nord	NA	*Lolium sp., Poa* sp.; *Festuca* sp.; *Pyracantha* spp.; *Ligustrum* spp.; *Crataegus* spp.; *Berberis* spp.; *Acer* spp.;*Carpinus* spp.*; Populus* spp.; *Tila* spp.; *Quercus* spp.; *Carpinus betulus; Prunus avium; Acer* spp.; *Tila* spp.*; Populus* spp.	NA	1060[3]	Nicese et al., (2021)
Rome	Park of Castel di Guido	AIRTREE	*A. campestre; Acer negundo; A. cordata; C. atlantica;C. australis; C. sempervirens; Eucalyptus* spp.; *Fraxinus angustifolia; F. ornus; Juglans nigra; Julans regia; Malus Sylvestris; Ostrya carpinifolia; Pinus eldarica; Pinus halepensis; Pinus pinaster; Pinus pinea; Populus nigra; Prunus avium; Pyrus amygdaliformis; Pyrus pyraster; Q. cerris; Quercus frainetto; Q. ilex; Q. pubescens; Q. robur; Quercus suber; Quercus trojana; R. pseudoacacia; Sorbus domestica*	NA	3875	Fares et al., (2020)
Turin	Park of Valentino	AIRTREE	*A. alba; Abies nordmanniana; Acer* spp.; *Aesculus hippocastanum; Alnus glutinosa; Carpinus betulus; Cedrus* spp.; *Cercis* spp.; *Chamaecyparis lawsoniana; Corylus avellana; Criptomeria japonica; F. sylvatica; Fraxinus excelsior; Ginko biloba; Ilex aquifolium; Juglans nigra; Lagerstroemia indica; Libocedrus decurrens; Liquidambar styraciflua; L. tulipifera; Magnolia grandiflora; Magnolia obovata; Malus* spp.; *Metasequoia glyptostroboides; Picea* spp. *Pinus* spp.; *Platanus* spp.; *Populus* spp.; *Prunus* spp. *P. menziesii; Quercus* spp.; *R. pseudoacacia; Salix babylonica; Sophora japonica; Sterculia platanifolia; T. distichum; Tilia* spp.;*Ulmus pumila; Zelkova carpinifolia*	NA	22,6	Fares et al., (2020)
Strasbourg	Strasbourg	i-Tree	London plane; Horsechestnut; European beech; European ash; English oak; Norway maple; Japanese pagoda tree; Crimean linden; Bigleaf linden; Cedar of lebanon; Greenspire linden; Sycamore maple; Silver linden; White willow	NA	88,23	Selmi et al., (2016)
Lugo	Vegetated areas along Miño, Rato y Fervedoira rivers	NA	*Acer pseudoplatanus; Quercus robur;Populus alba;Myscanthus;* Galician varieties of chestnut; Galician representative trees and shrubs; Cabbage; Turnip; Potato; Lettuce	NA	495,98	De la Sota et al., (2019)

[1] Worst case scenario of carbon removal in Bristol, [2] Best case scenario of carbon removal in Bristol, [3] Carbon stored by the woody areas

3.2. Factors controlling the capture of CO_2 by urban forest

The analysis of the different cases studies has raised some important factors controlling the capture of CO_2 from the atmosphere of the urban forest in European cities. These factors can be classified as factors related to the tree characteristics and factors related to the management.

Factors related to tree characteristics

The species living in a vegetated area affect the removal and sequestration of carbon as the results of Soares et al., (2011) show. Taking into account the amount of CO_2 that every species can sequester and the CO_2 emitted due to the maintenance of the species they arrived at the conclusion that the trees that removed more carbon dioxide from the air in Lisbon are: *A. negundo, Platanus spp., P. nigra, Populus×canadensis,* and *F. angustifolia* and the species that captured the least amount of carbon dioxide are *K. paniculata* and *J. mimosifolia*. The structural and ecophysiological characteristics of vegetation are also a factor controlling the CO_2 concentration on-air as seen by Fares et al., (2020). If the trees are evergreen or deciduous is also a factor that controls the concentration of carbon dioxide in the atmosphere as seen in Fares et al., (2020). In the study, evergreen trees showed a higher NPP (net primary production), the net carbon assimilated via photosynthesis.

The size of trees is another important factor to take into account. Walters & Sinnett, (2021), studied different scenarios of tree sizes in Bristol. In all the scenarios tested, bigger trees sequestrated a bigger amount of carbon tons. The variation of carbon sequestrated by trees depending on their size is different depending on the different scenarios. The highest difference goes up to 65129.5 tons of carbon dioxide sequestered by 2045.

The month and season of the year may have an influence on the sequestration of carbon. Selmi et al., (2016) show that in Strasbourg, France, the month in which the removal of CO is higher is in September. In September 2012 0,26 tons of CO were removed. The study also shows that during the in-leaf season the removal of air pollutants is higher.

The number of woody plants in urban forests controls the removal of carbon dioxide from the atmosphere as the greatest part of the carbon stored on trees is stored in their wooden parts. Nicese et al., (2021) showed that the green typology that stored the highest amount of CO_2 along the 50 years of analysis was the afforested area as it had up to 100 ha of wooden area. However, tree rows were more efficient in storing 72 Kg/m^2.

The mortality of the trees in the urban forests has an effect on the removal of carbon dioxide from the atmosphere. Walters & Sinnett, (2021) made their simulations with two different annual mortality percentages, 0.5 %, and 3 %. In all the scenarios simulated, the total carbon removed from the atmosphere by the urban trees is higher when the mortality percentage is 0.5 %. The difference of tons of CO2 removed from the atmosphere varies significantly depending on the mortality (3 % or 0.5 %) in all the scenarios studied. The highest difference is in scenario 4, which consists in planting 10000 large trees per year, with a difference of 543855,2 tons of carbon dioxide sequestered by 2045 and the smallest difference is in scenario 9, which consists in planting intermittently every five years medium trees, with a difference of 134666,4 tons of carbon dioxide sequestered by 2045.

All the factors stated above are the factors related to the species of the vegetation that form the green areas in cities and surroundings. But there is another group of factors that controls the sequestration of carbon from the air. These are the factors related to management.

Factors related to management

The use of fertilizers and pesticides has an impact on the accumulation of CO2 in the atmosphere. As seen in De la Sota et al., (2019) the use of pesticides, fertilizers, and other inputs give off the 15 % of the emissions due to vegetation management, so they reduce the net balance of CO_2 removal.

Land use and the management needed according to this land use has an impact on the carbon sequestered by the trees inhabiting the area. The study of De la Sota et al., (2019) showed that different uses of land (i.e. urban agriculture and urban forest) need different management and the management emits different air pollutants. This management includes machinery, transport, inputs (pesticides, fertilizers, etc.), and irrigation. Nicese et al., (2021) studied 5 different green typologies (lawns, hedges, social allotments, tree rows, and afforested areas) that needed different management. Four of the green typologies had a positive impact taking into account the emissions due to their management and the amount of carbon dioxide that they were capable to remove. Hedges were the ones that had a negative impact and it was due to the management needed, two interventions per year during 45 years.

The planting strategies are an important factor that can help reduce the carbon footprint. Walters & Sinnett, (2021) showed that depending on the planting strategy followed in an urban forest affects the amount of carbon sequestered by trees, in this scenario trees can sequestrate up to 302,043.0 tons of carbon by 2045.

Finally, an important factor is the area of the vegetated areas. Nicese et al., (2021) show that social allotments have a smaller positive area than the other typologies with a positive carbon balance due to the small area of the social allotments, which is 25 m^2.

3.3 Effects of CO_2 concentration on the growth of urban forest

The articles analyzed in this part are from cities and countries over the world: Houston, Hanoi, Sapporo, Rio de Janeiro, Shenyang, São Pablo, Araucaria, and Caserta. These studies make comparisons between the growth of urban trees and rural trees, comparisons between industrialized areas and non-industrialized areas in the same city, analysis of their own measurements following typical dendrochronological methods, and analysis from the trees that live next to main roads and are very exposed to traffic pollution. These studies have analyzed the effect of carbon dioxide concentration in the air on the growth of urban forests.

Table 2. Summary of the articles analyzed for the second objective of the review indicating the city, the study area, the specie and the number of trees studied in each article

City	Study area	Specie	Number of trees	Reference
Araucaria	Residential zone; Steel company; Petroleum refinery; Downtown	*Angustifolia*	144	(Canetti et al., 2017)
Sapporo	Shirahata-yama 1 (rural); Shirahata-yama 2 (rural); Misumai of Hokkaido University Forests (rural); Hokkaido University Nursery (urban); Hitsujigaoka-7 (suburban)	*Abies sachalinensis*	109	(Moser-Reischl et al., 2019)
Houston	Urban (less than 4.5 km from the city center); Suburban (less than 9.5 km from the coty center); Rural (more than 9.5 km from the city center)	*Q. nigra*	183	(Moser et al., 2017)
Caserta	Via Marconi; Via Campania	*Pinus pinea*	7	(Battipaglia et al., 2010)
São Paulo	Metropolitan region of São Paulo	*Tipuana tipu*	41	(Locosselli et al., 2019)
Rio de Janeiro	Reserva Biológica do Tinguá (forest site); Fundação Oswaldo Cruz (urban site)	*Ceiba speciosa*	25	(Vasconcellos et al., 2019)
Hanoi	Dong Ang (rural, suburban); Dan Phuong (rural); Hoai Duc (rural); City center (urban, suburban)	*Khaya senegalensis*	149	(Moser-Reischl et al., 2018)

There are several factors that can affect tree growth in cities and can be classified into three groups: factors related to pollution (air pollutants), factors related to the management (location of the vegetated area), and factors related to tree characteristics (size and age).

Factors related to pollution

A very important factor that affects tree growth related to pollution is the concentration of air pollutants. Some of the air pollutants allow trees to grow faster while other air pollutants have the opposite effect. Locosselli et al., (2019) found out that in São Paulo trees grow faster in the zones with a higher concentration of airborne P while they grow slower in the zones with a higher concentration of Al, Ba, Zn, and PM_{10}. However, they also found that in the city as the temperature increases trees grow faster. The rise of temperature is related to the concentration of air pollutants and greenhouse gases. Canetti et al., (2017) show that the growth of *Angustifolia* of 20 – 60 cm of dbh (diameter at breast height) has a positive correlation with the concentration of SO_2 and a negative correlation with the concentration of NO. Moser-Reischl et al., (2019) found out that in Sapporo *Abies sachalinensis* grow faster when the concentration of NO_x, SO_2, O_x, CO, and NO_2 (in this case the relation is weaker) while the concentration of oxides has the contrary effect. In Caserta, Battipaglia et al., (2010) studied the growth of trees between 1980 and 2010, near a heavily polluted road, where traffic increased a 64 % since 1980. As the traffic has increased the exposure to air pollutants has also gone up. The study shows the ring width of the trees studied from 1934 to 2004 and the decrease of the ring from 1980 to 2004 is considerable. Locosselli et al., (2019) show that the concentration of air pollutants such as PM_{10} and airborne Al, Ba, and Zn influence tree growth dramatically making trees grow slower.

Factors related to the management

The second group of factors is related to the management of the urban forests and green areas in the city periphery. The location of the vegetated area is also a factor to take into account as the exposure to air pollutants depends on the location of the vegetation in the city. Several of the studies mentioned in Table 2 has analyzed trees from the city and also from rural zones nearby. Moser-Reischl et al., (2019) studied different sites in Sapporo classified as urban, suburban, and rural. Their results show that rural trees were the oldest with an average age of 100 years. They had the biggest values of dbh, crown diameter, and crown volume. Urban and suburban trees showed similar results. Nevertheless, the younger ones were suburban with an average age of 35 years. The suburban trees had the smallest values of dbh, crown diameter, and crown volume. Several studies reveal that urban trees grow faster when they are younger. That happens because in cities the concentration of carbon dioxide and temperature is higher, so the growing season is prolonged. Though, this has a negative effect as they die sooner. So in the long term, rural trees grow faster and in better conditions (Moser et al., 2017; Moser-Reischl et al., 2018; Vasconcellos et al., 2019).

Also related to location, an important factor is the place of the urban forest inside the city. Canetti et al., (2017) identify four different areas of the city in which *Angustifolia* was studied (Table 2). The obtained results show that *Angustifolia* lately are having the tendency to grow slower. However, studying the four areas separately, they arrived at the conclusion that near the Petroleum refinery the tendency of the trees is to grow faster.

Factors related to tree characteristics

The third and last group of factors that affect tree growth due to the exposition to air pollutants are those related to trees' characteristics. The diameter at breast height (dbh) is a factor to take into account. Canetti et al., (2017) suggest that depending on the dbh of trees, their favorable area to grow at a faster rate might change. The research studied trees from four different zones dividing the trees into 3 different classes depending on the dbh size. While the largest (60 – 80 cm of dbh) and medium (40 – 60 cm of dbh) trees had the fastest growth at the Petroleum refinery zone, the smallest ones (20 – 40 cm of dbh) experienced the fastest tree growth in rural areas and also in residential neighborhoods. In all cases, the further is the zone from the center of the city, the greater is the average growth per year. Nevertheless, the study shows that younger trees are more affected by pollution than older trees. In fact, another factor that has been already mentioned is the age of the urban forest. For instance, Moser-Reischl et al., (2019) showed that in the city trees around 60 years old grow faster than in the rural areas, while after 100 years they grow faster in the forest.

4. Conclusion

In this research, I have analyzed the relation between urban forests and pollution and how they affect each other. Different researches had been made about either of the relations mentioned, however, there aren’t studies that analyze both at the same time, as this review does. That’s why my research has had two different parts.

In the first part, I have focused my attention on the effects of urban forests on pollution, observing how urban forests can be very effective to mitigate global warming by reducing the greenhouse gases and other pollutants concentration from the atmosphere. To explain so I have analyzed articles from all over Europe. Those researches mentioned several factors controlling the CO_2 removal of the atmosphere that can be classified into those related to tree characteristics and those related to the management of urban forests. This was the end of the first objective presented in the introduction.

After that, I analyzed the effect that air pollution has on tree growth. To do so, I reviewed studies from all over the world. The studies reveal that in cities trees tend to grow faster due to the carbon dioxide concentration, the increase in temperature, and the prolonged growth seasons due to global warming. However, this also translates into faster aging and sooner death. In summary, I found that tree growth in urban forests is influenced by factors related to pollution (air pollutants), factors related to the management (location of the vegetated area), and factors related to tree characteristics (size and age).

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