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Extensive green roofs as a strategy for air pollution abatement in Barcelona

Cubiertas verdes extensivas como estrategia para mejorar la calidad del aire en Barcelona

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Bachelor Thesis

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Roof gardens are meant for the recovery of all the built-up area. Therefore, the flat roof demands in the first place systematic utilization for domestic purposes: roof terrace, roof garden.

Le Corbusier, *Towards an architecture*
1923

Abstract

Green roofs are frequently promulgated for its environmental, economic, and social benefits. Extensive green roofs involve growing small plants with an adequate structure on rooftops and are one tool that can help mitigate the negative effects of air pollution on urban areas. This study encompasses published research to date on how green roofs can help mitigate pollution and quantifies the level of air pollution removal of extensive green roofs in two possible future scenarios in the Barcelona urban center. The focus was laid down on pollutants with health-threatening levels during the year 2020. A dry deposition model like the i-Tree Eco software was used to estimate how much pollution can be absorbed. The results showed that a total of 81,469 kg of NO_2 and 35,587 kg of PM_{10} can be removed annually by the first scenario and consequently, a total of 1.2 metric tons of NO_2 and 53,380 kg of PM_{10} can be removed annually by the second scenario. Although expensive, green roof construction may be justified if the environmental advantages and different government subsidies were taken into account. This research suggests green roofs have the potential to play a key role in the development of sustainable cities, and as a result, they should be widely employed and promoted as instruments in urban planning and policies towards a climate friendly future.

Con frecuencia las cubiertas verdes son aclamadas por sus beneficios medioambientales, económicos y sociales. Las cubiertas verdes extensivas consisten en el crecimiento de plantas pequeñas con una estructura adecuada encima de tejados, siendo una herramienta capaz de mitigar los efectos nocivos de la contaminación en áreas urbanas. Este estudio engloba investigación realizada hasta la fecha sobre como las cubiertas verdes pueden ayudar a reducir la contaminación y cuantifica cuánta polución pueden eliminar los tejados verdes extensivos en dos posibles escenarios en el área metropolitana de Barcelona. El foco se ha centrado en los contaminantes que presentaron niveles nocivos para la salud durante el año 2020. Se ha empleado un software que utiliza un modelo de deposición seca para estimar cuánta contaminación puede ser eliminada. Los resultados muestran que el primer escenario puede llegar a eliminar un total de 81,469 kg de NO_2 y 35,587 kg de PM_{10} durante un año. El segundo escenario planteado puede llegar a eliminar un total de 1.2 toneladas de NO_2 y 53,380 kg de PM_{10}.

A pesar de mostrar un coste elevado, la construcción de cubiertas verdes puede llegar a justificarse gracias a sus ventajas medioambientales, teniendo en cuenta además la existencia de diferentes subsidios públicos para su construcción. Esta investigación sugiere que los tejados verdes tienen el potencial de jugar un papel fundamental en el desarrollo de ciudades sostenibles, y como consecuencia deberían desarrollarse y promocionarse como infraestructura urbanística clave junto a políticas medioambientales que nos acerquen a un futuro más sostenible.

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Acronyms and Abbreviations

ºC	Degrees Celsius
$\mu g/m^3$	Microgram (one millionth of a gram) per cubic meter
$\mu g/m^2$	Microgram (one millionth of a gram) per square meter
mg	Milligrams
AQEG	Air Quality Expert Group
ASPB	*Agencia de Salut Pública de Barcelona*
BCC	Barcelona City Council
C40	Network of 97 world cities against climate change
C_4H	Methane
CHF	Swiss Franc
cm	Centimeters
CO_2	Carbon Dioxide
CO	Carbon Monoxide
COP21	The 21st Conference of the Parties
CREAF	*Centro de Investigación Ecológica y Aplicaciones Forestales*
DC	Directorate-General
EC	European Commission
ECCC	Environment and Climate Change Canada
EEA	European Environment Agency
EFB	European Federation Green Roofs & Walls
EGLE	Michigan Department of Environment, Great Lakes and Energy
EPA	United States Environmental Protection Agency
EU	European Union
GDP	Gross Domestic Product
GISS	Goddard Institute for Space Studies
GR	Green Roof
GRaBS	Green and Blue Space Adaptation for Urban Areas and Eco Towns
GRHC	Green Roofs for Healthy Cities
h	hours
IFB	The Hamburg Investment and Development Bank
IPCC	Intergovernmental Panel on Climate Change

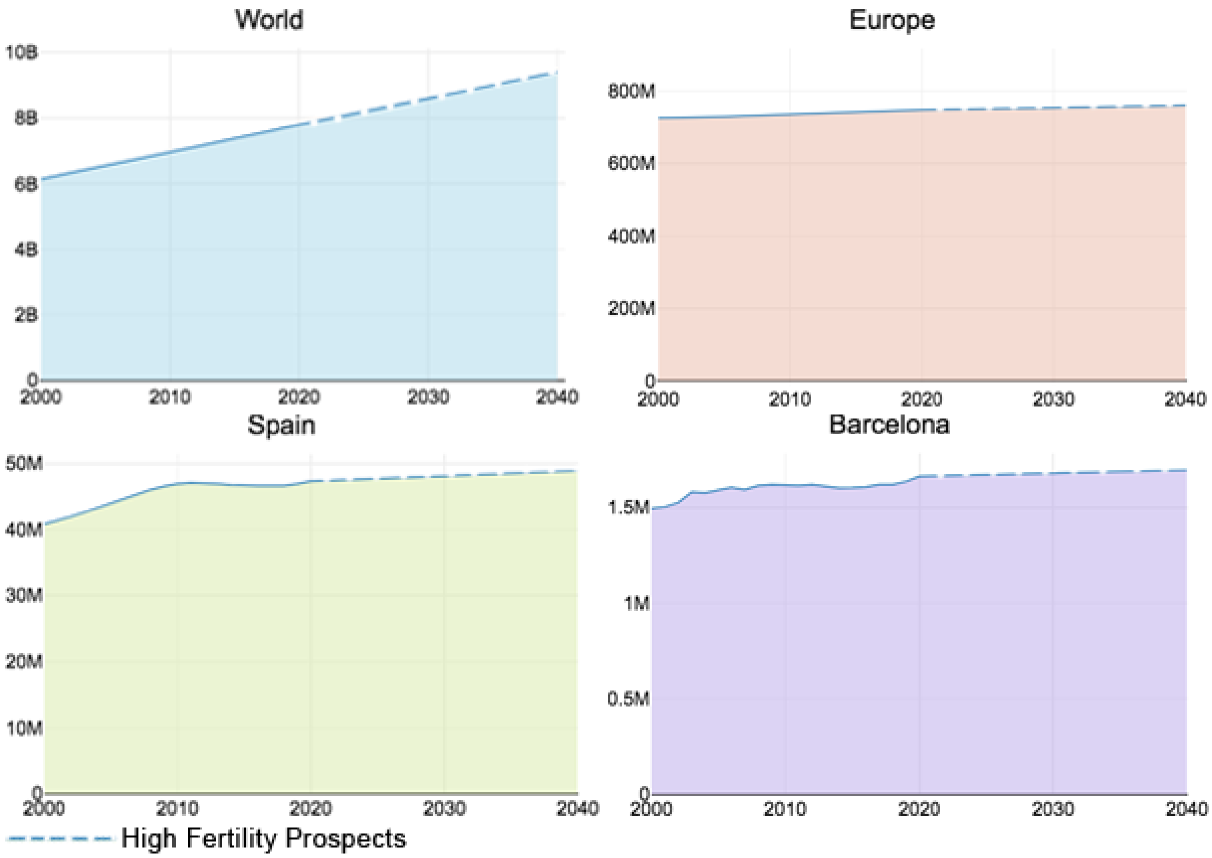
kg/ha	Kilogram per hectare
MITECO	*Ministerio para la Transición Ecológica y el Reto Demográfico*
MT	Megatonnes
N2O	Nitrous Oxide
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
Nr.	Number
NRDC	Natural Resources Defense Council
NSIDC	National Snow and Ice Data Center
O_3	Ozone
$PM_{2,5}$	Particulate Matter with a diameter less than 2.5 micrometers
PM_{10}	Particulate Matter with a diameter less than 10 micrometers
ppm	Parts Per Million
SO_2	Sulfur Dioxide
T	Tonne
UFORE	Urban Forest Effects Model
UN	United Nations
UN DESA	United Nations Department of Economic and Social Affairs
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USDA	United States Department of Agriculture
WHO	World Health Organization
ZBE	*Zona de Bajas Emisiones*
ZHAW	Zurich University of Applied Sciences Wädenswil

List of Figures & Tables

1. Introduction

In 2020, 7.7 billion people live on planet earth, with an average population growth rate of 1.2% since the year 2000. Levels of population continue to grow significantly. More than half of the world's total population (4 billion) live in urban areas around the globe. Although the average annual rate of growth of the world urban population has lowered by 0.4 points since 2000, the UN predicts that by 2050 more than two-thirds of the world population will live in cities with a total global population of almost 10 billion (UN, 2021).

Fig. 1.1. Population growth in the last 20 years & High Fertility Variant Prospects

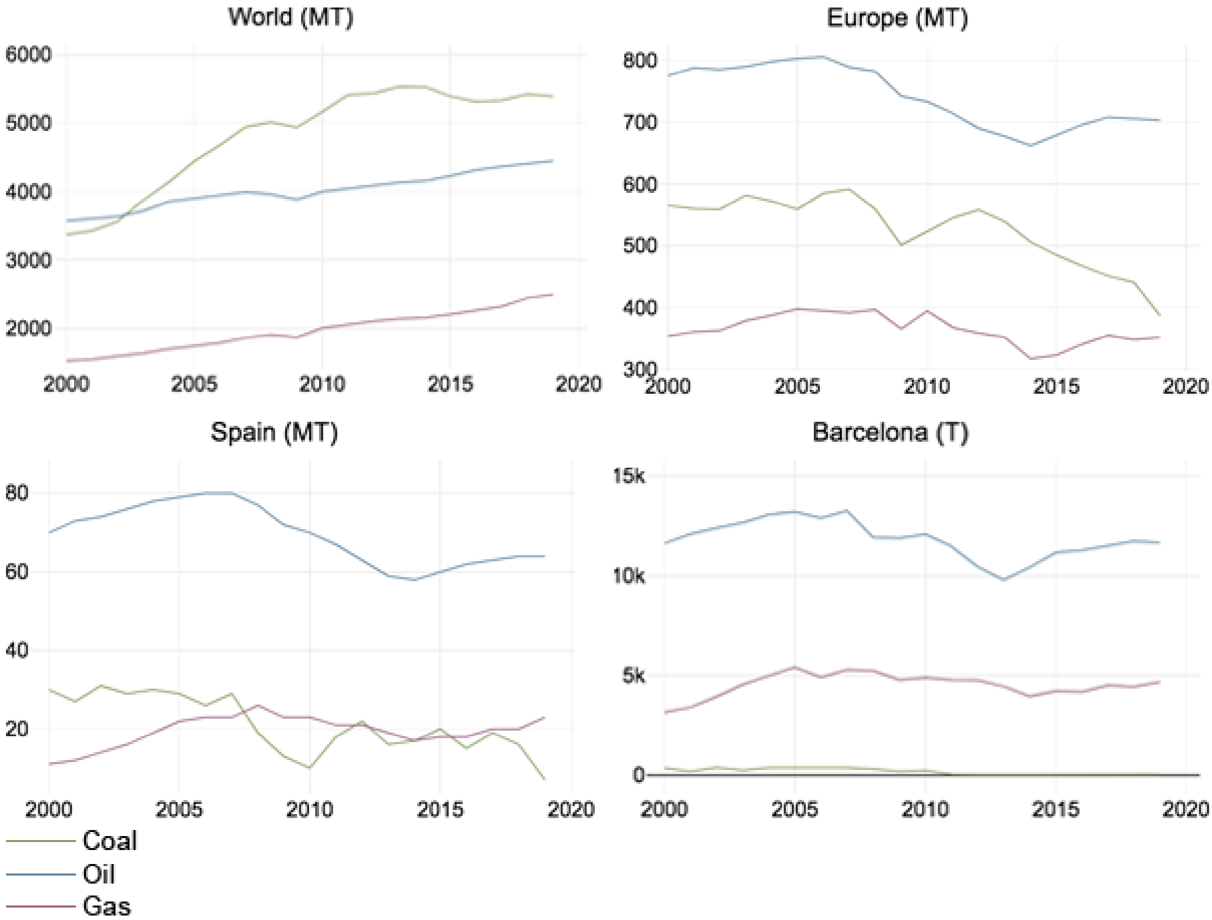


Source: Self creation. Data extracted from: UN World Population Prospects, 2019 & National Statistics Institute, 2020

Cities only occupy 2% of the world's surface. But their climate impact is enormous. All world cities consume together over two-thirds of the world's energy and are responsible for more than 70% of the total greenhouse gases emissions (C40, 2021). The emission of greenhouse gases is the main cause of global warming and climate change. Greenhouse gases are mainly composed by carbon dioxide (CO_2)[1], methane (CH_4), nitrous oxide (N_2O) and fluorinated gases. All of them are expelled to the atmosphere through the production, transport and consumption of fossil fuels like oil, coal and natural gas. Livestock and agricultural processes are also linked to the emission of these gases, comprising only 10% of the total greenhouse gas emission (EPA, 2020).

The production and burning of fossil fuels has had a negative impact on an environmental level by raising the global temperature by 1ºC. 2020 took the second place behind 2016 as the record of the warmest year (NOAA, 2021).

Figure 1.2. Fossil fuels consumption from 2000 to 2019 (MT: Megatonnes & T: Tonne)



Source: Self creation. Data extracted from: BP Statistical Review of World Energy, 2019 & Catalan Institute of Energy, 2020.

[1] CO_2 is a by-product of fossil fuel combustion and it is often held responsible for climate change, because it is one of the atmospheric gases that prevents terrestrial energy from escaping into space, leading to higher temperatures due to the greenhouse effect.

An overall slight decrease in the consumption of fossil fuels indicates that many countries, governments and institutions recognize the problem of global warming and that measures against it are starting to show some results. Energy originating from renewable sources has increased during the last 10 years. However the current levels of fossil fuel consumption are still immense and concerning. Based on the current world fossil fuel consumption trajectory, temperatures and air pollution will continue to rise especially in urban areas, since 68% of the world's inhabitants will live in urban areas by 2050 (UN DESA, 2018). Greenhouse gases and air pollution produced in the past 140 years can stay for long periods of time in our atmosphere. Specifically CO_2, can stay between 300 to 1,000 years in earth's atmosphere. Knowing that half of the increment of CO_2 concentrations in the last 300 years has occurred since 1980 (EPA, 2020; NASA, 2019), illustrates a steeper trajectory of change towards an environmentally-friendly future.

Besides the negative effects on our climate, the burning of fossil fuels increases the levels of air pollutants and greenhouse gases. Through the combustion of fossil fuels, chemicals like ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), methane (CH_4), benzopyrene (BaP) and particulate matter[2] ($PM_{2,5}$,PM_{10} as soot and fly ash) will be present in the air we breathe. These air pollutants have a detrimental impact on our physical health. In high-income countries, urban outdoor air pollution is one of the top ten health risk factors (WHO, 2018).

The World Health Organization updated estimates show that urban air pollution caused a total of 7 million premature deaths per year in developing countries (WHO, 2018). To compare, COVID19 has caused 1.69 million deaths worldwide (WHO, 2020) which is 76% fewer deaths than caused by air pollution. These numbers raise questions such as; what will lead to reductions in air pollution, are governments addressing this with the resources necessary to facilitate a reduction in air pollution, are the reductions indicated in the Paris c Climate Accord sufficient to impact climate change and should this be considered a global pandemic?

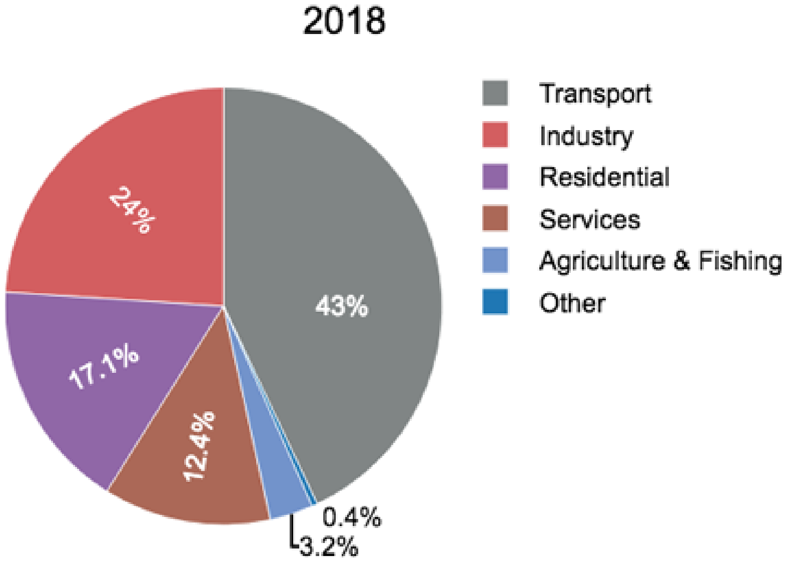
[2] PM_{10} particles have been found travelling deep into the lungs, causing inflammation and aggravating the symptoms of people with heart and lung diseases. $PM_{2,5}$ particles are smaller in diameter, therefore being a subset of PM_{10} particles. Since they may be pulled deeper into the lungs and can be more harmful, their negative health effects are more severe (Hime et al., 2018).

In September of 2020, the EEA published its annual 'Air quality in Europe' report. The results of health impact calculations for 2018 of the 41 European listed countries show that 492,600 premature deaths are attributed to air pollutants. Spain together with Italy, Germany, France and Poland are in the top five countries where air pollution causes the largest impact on mortality in the population. With more than 31,000 premature deaths in 2018 associated with air pollution (EEA, 2020).

Air pollution affects all life cycles, including pregnancy. Studies show that it leads to damages with the neuronal and respiratory development of infants (WHO 2013a, WHO 2013b). Atmospheric contamination is carcinogenic for humans. In 2010, 223.000 lung cancer deaths were related to air pollution (WHO 2013). Moreover, according to the WHO , exposure to air pollution has been linked to type 2 diabetes, obesity, systemic inflammation, Alzheimer's disease, and dementia (WHO, 2016). In addition, a study conducted in Italy looked at a possible link between air pollution and potential effects on mental health. The study, published at the Cambridge University Press, found a statistically significant positive correlation between high ozone levels and admissions to psychiatric emergency services (F.Berdardini, L.Attademo, 2019).

Following the UNFCCC, the Kyoto Protocol and the EU Regulation 525/2013, the Spanish government discloses a yearly report about its greenhouse gas emissions and other relevant information about climate change. The biggest greenhouse gas is CO_2 with 260 MT expelled to the atmosphere in 2019. In addition, air pollution limit values set by the EU Commission have been surpassed in Madrid, Granada and Barcelona metropolitan areas (MITECO, 2020).

Figure 1.3. Spain Final Energy Consumption by Sector in 2018



Source: Self creation. Data extracted from: MITECO, 2019

The biggest source of greenhouse gases in Spain comes from transport. Almost all types of transport take place in main Spanish urban hubs like Madrid, Barcelona, Valencia or Sevilla; where road infrastructure, airports, maritime ports and industrial facilities are located.

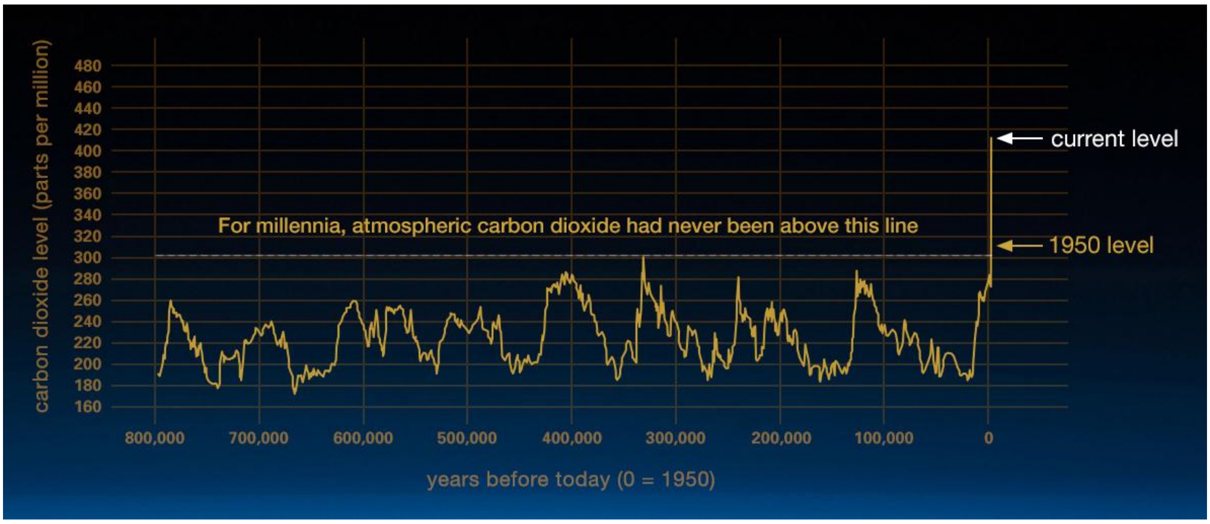
The growth in the world's population brings us to an expansion or densification of urban areas. This means that more generations will be exposed to contaminated air in urban areas. As these urban areas desify, additional energy and resources will be needed to supply an increasing demand of a growing population.

As a result, cities with serious air pollution issues must devise strategies to control the problem and mitigate the damage. Cities, as part of the climate change issue, have the opportunity to play an important role in its resolution. Urban centers are at the forefront of global climate change, and they are also well-positioned to play a leadership role in driving global climate action. City governments are often more in tune with their businesses, residents, and institutions than state and national governments, allowing new policies to be enacted more quickly and decisively.

1.1. Current Climate Situation

Historical atmospheric compositions samples from millions of years ago can be found in the polar ice sheets. Scientific evidence like the following three figures show a direct cause-effect correlation between CO_2 levels and globally rising temperatures.

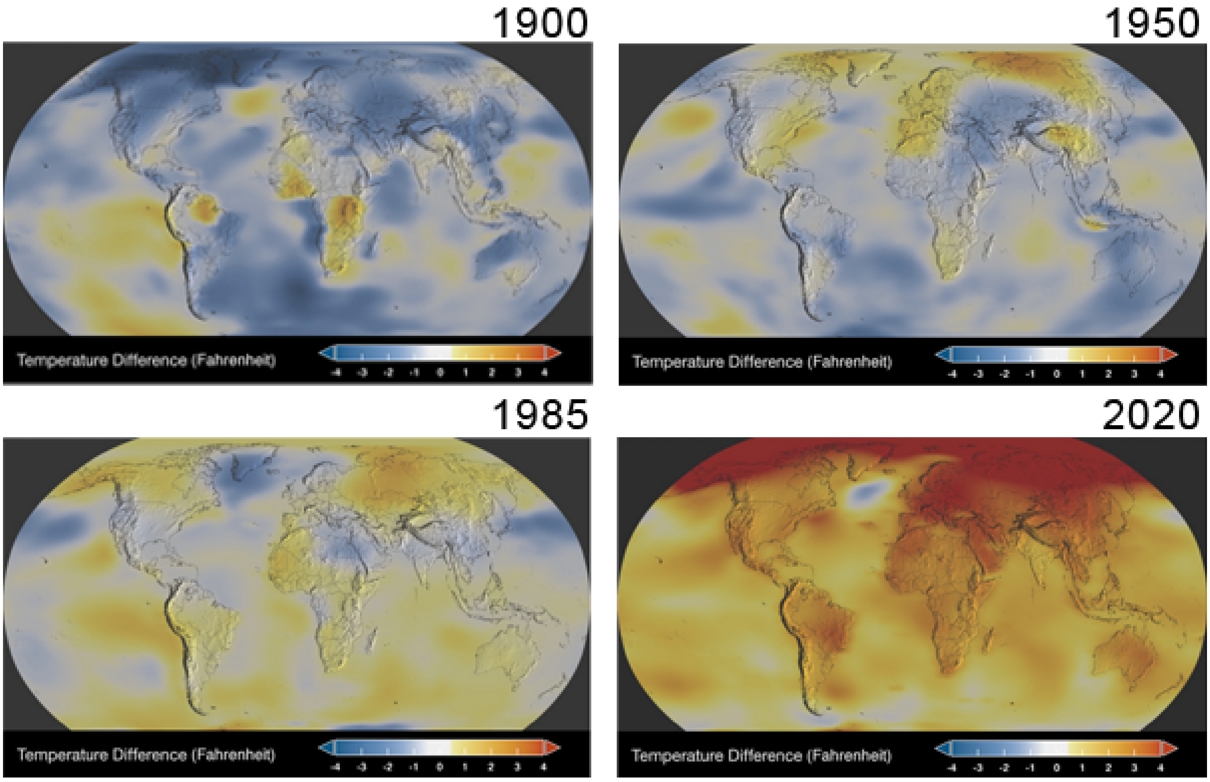
Figure 1.4. Historical atmospheric CO_2 levels found in polar ice



Source: NASA, 2021

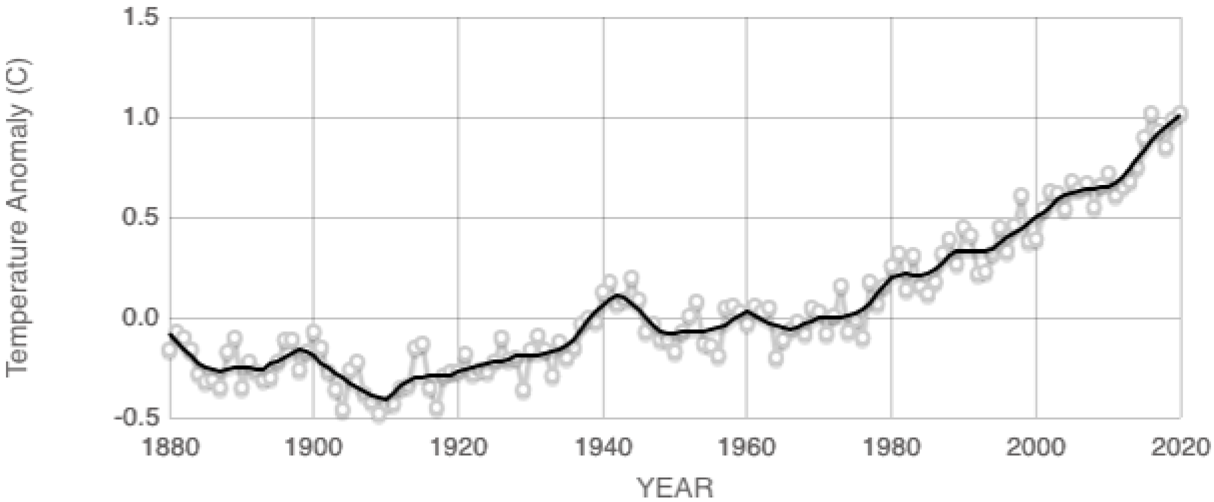
Figures below illustrate the change in the global surface temperature relative to 1951-1980 average temperatures. The Paris Agreement takes the average temperature between these years also as a reference to limit global rising temperatures. Temperatures going above or below this average are considered as anomalies.

Figure1.5: Five-year average variation of global surface temperatures



Source: NASA/GISS, 2021

Figure 1.6: Global Land-Ocean Temperature Index



Source: NASA/GISS, 2021

The existence of a human caused global warming is irrefutable. Data shows a rapid warming in the past decades and several reports conducted in peer-reviewed scientific journals illustrate that more than 97% of currently reporting climate scientists agree on global warming (Cook, 2016). Two degrees Celsius may seem insignificant, but it is a rare occurrence in our planet's recent history. The global average temperature is constant over long periods of time, according to the climate record preserved in tree rings, ice cores, and coral reefs. Furthermore, minor temperature variations result in massive changes in the atmosphere. E.g., during the last ice age, when large northern areas of the European, Asian and American continents were covered by almost one kilometer of ice, average temperatures were about 6º Celsius colder than today (Nature, 2020).

Right now the effects of one degree global warming can be seen in the arctic sea ice minimum surface with a decrease of almost 50% of its surface compared to the levels in 1980. Each year the Antarctic and Greenland regions lose approximately 215 billion tonnes of its ice mass. This has a direct effect on sea levels, which rise 3.3 millimeters per year. The first NASA satellite sea level measurement started on January 1993, the last measurements show an increase of 96 millimeters or ~3.8 inches since then (NSIDC/NASA, 2020). If this path is kept, by 2050 ocean and sea levels will rise almost 20 centimeters. A study found that by 2050 mainland China, Bangladesh, India, Vietnam, Indonesia, and Thailand are the countries where most people will live in homes under the annual average flooding level. This study modeled its findings with globally moderate greenhouse gases emissions cuts and concluded that more than 300 million people will live under serious flooding danger in 2050. In other words, 8.7% of those nations habitants will live under potentially flooding conditions (Kulp and Strauss, 2019).

Countries, governments and institutions are already seeing the effects of these small climate changes in the form of shorter and warmer winters, longer and hotter summers, changes in precipitation patterns, more droughts and heat waves, hurricanes and typhoons becoming stronger and more intense, and desertification propensity.

The IPCC has stated over the last years that: *"Taken as a whole, the range of published evidence indicates that the net damage costs of climate change are likely to be significant and to increase over time."* Several peer-reviewed studies published these last years, show accurate estimations on which economic costs and damages can climate change and its mitigation cause in the future.

It is known that actions needed to mitigate climate change may not be cheap, but the cost of not acting will be much greater. Studies show that if the actual global trend continues, the total cost of global warming will be as high as 3.6% of the global GDP. In the US only, four global warming impacts alone —hurricane damage, real estate losses, energy costs, and water costs— will come with a price tag of 1.8% of the United States GDP, or almost $1.9 trillion annually by 2100 (NRDC, 2008). Another study conducted by Sanderson, B.M., O'Neill, B.C. suggested that our historical inaction on climate change could lead us to a net cost of 15- to 35% of global GDP (13- to 30 trillion $) by 2100 (Nature, 2020).

1.2. Paris Agreement - 2030 Climate & Energy Framework

The Paris Agreement, which was approved at the Paris Climate Conference (COP21) in December 2015, is the very first universal, legally enforceable global climate change agreement. 55 countries responsible for 55% of the global greenhouse gas emission were needed to approve, accept and ratify the Agreement. In October of 2016 this threshold was reached and the legal enforcement of the Paris Agreement was accomplished. Currently, 191 out of 197 countries agree on the acceptance and ratification of the agreement. Eritrea, Iran, Iraq, Libya, Turkey and Yemen have not declared their ratification of the agreement. In November of 2019, the United States withdrew under a new administration, on January 21 2020, the US re-entered the agreement and has committed to be an active member of the agreement (UN, EC, 2021). The US president stated and signed the following: *"I, Joseph R. Biden Jr., President of the United States of America, having seen and considered the Paris Agreement, done at Paris on December 12, 2015, do hereby accept the said Agreement and every article and clause thereof on behalf of the United States of America."*

The US is the second most CO_2 producing country in the world, with 13.4% of the global emissions after China. Therefore US rejoining the Agreement sheds some light towards an environment friendly future for the generations to come. This global agreement is considered to be the bridge linking today's global policies and climate-neutrality before the XXI century ends.

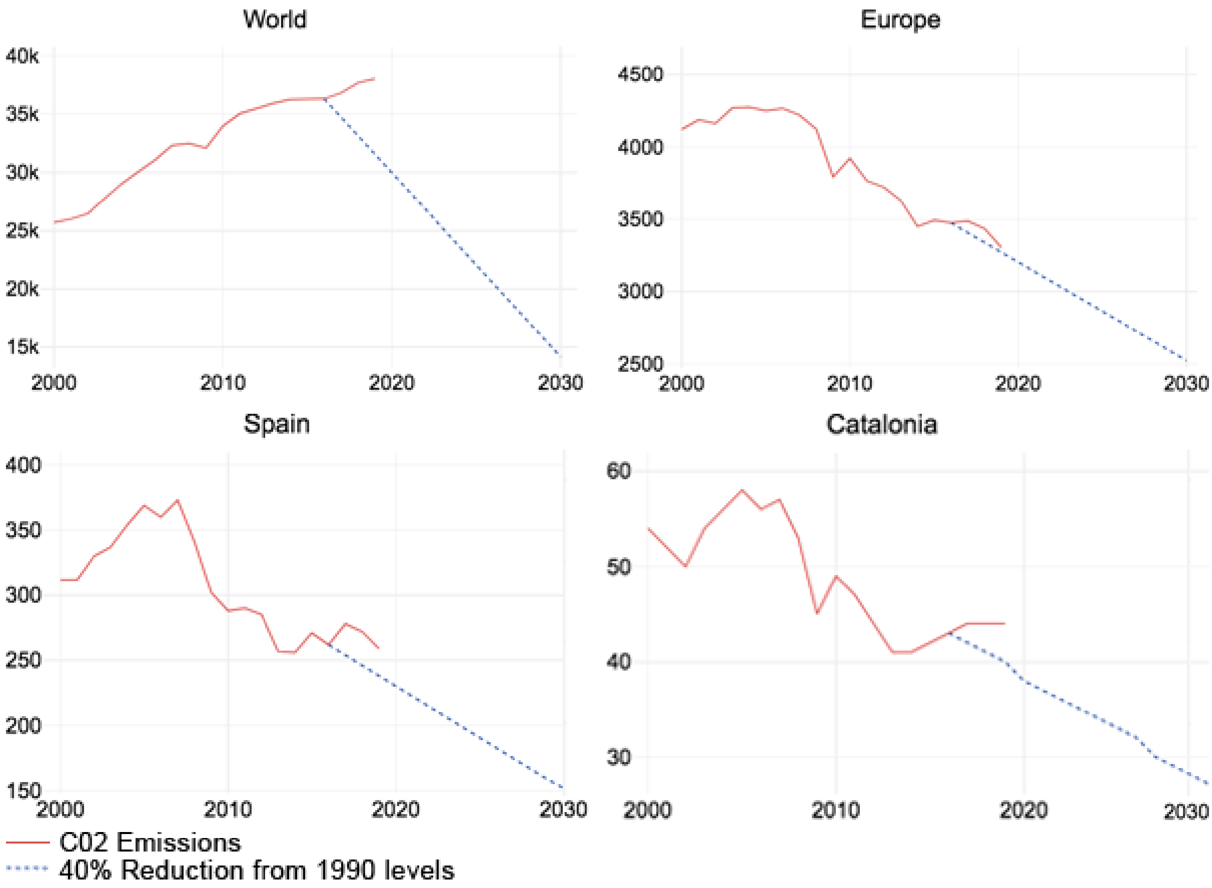
"The Paris Agreement sets out a global framework to avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C. It also

aims to strengthen countries' ability to deal with the impacts of climate change and support them in their efforts."

The Paris Agreement has set three different key factors to maintain global warming below the limit of 2ºC as per 2050:

- At least 40% reduction in greenhouse gas emissions (from 1990 levels)
- At least 32% share in renewable energy

Figure 1.7. CO_2 Emissions from 2000 to 2019 & the 40% cut form 1990 levels (MT)



Source: Self creation. Data extracted from: EC & MITECO, 2020

1.2.1. European Commission & WHO - Air Quality Standards and Guidelines

The European Commission has been working together with the EEA and WHO since the 1970s in order to establish the correct policies and instruments to improve air quality in the European Union. The actual working legislation is based on EC Directives since 2004, nonetheless the lay down of active rules and its implementation did not happen till 2011. Centered on recent research on air pollution's health effects, the Ambient Air Quality Directives of the EC has set the following air quality standards.

Table 1.1. EC Air Quality Standards

Pollutant	Concentration	Averaging period	Permitted exceedances each year
PM2.5	**25 µg/m3**	1 year	*n/a*
PM10	**50 µg/m3**	24 hours	*35*
	40 µg/m3	1 year	*n/a*
Sulphur dioxide (SO2)	**350 µg/m3**	1 hour	*24*
	125 µg/m3	24 hours	*3*
Nitrogen dioxide (NO2)	**200 µg/m3**	1 hour	*18*
	40 µg/m3	1 year	*n/a*
Ozone (O3)	**120 µg/m3**	8 hours	*n/a*
Carbon monoxide (CO)	**10 mg/m3**	8 hours	*n/a*

Source: Self creation. Data extracted from: European Commission 2021.

European Legislation on air quality says that Member States should measure air pollution levels and report the following data to the EC. Where levels surpass the set standards, Member States should develop an air quality program to ensure compliance with the limit value. Furthermore, information on air quality of each area should be disseminated to the public (EC, 2021).

The WHO has set for two of the pollutants more exigent guidelines. In the case of PM_{10}, the annual average should not be higher than 20 µg/m^3 and in the case of O_3 the 8 hours average concentration should be under 100 µg/m^3 in order to comply (WHO, 2018).

1.3. Aims and literature review

Traditional air pollution management methods concentrate on lowering the source of air pollutants (EC, 2013). This approach effectively reduces the emission of new air pollutants while leaving existing pollutants free in the atmosphere. New methods can be implemented to eliminate existing air pollution thus diminishing pollutants concentration to acceptable amounts.

One such new method is the use of urban vegetation that can help reduce air pollution by a dry deposition process, microclimate effects and CO_2 absorption by photosynthesis (AQEG, 2018). Plants in general terms can have an indirect effect on the reduction of air pollution by changing existing inner city microclimates. Vegetation can reduce the indoor temperature of buildings through shading, thereby reducing the consumption of electric power for air conditioning during hot seasons. David J. Nowak (2006) discovered that urban vegetation, like trees in the U.S. cities, eliminates approximately 711.000 tons of pollution yearly.

While it is preferable to use trees to reduce pollution and absorb CO_2, planting trees in a densely populated city is not always possible. By 2017, Barcelona counted 1.4 million trees that represent 25% of the urban surface. This figure includes trees in big green areas like Collserola, Montjuïc and Tres Turons, located in streets and parks, and also in public and private gardens. Even with all these trees, Barcelona still consists of 75% of the city urban area without any green coverage (Barcelona City Council, 2017; CREAF, 2009). The implementation of green roofs can be a potential solution to this dilemma since it makes use of rooftops, commonly 40-50% of the impermeable area in big developed urban areas (Dunnett and Kingsbury, 2004). Furthermore, several studies on the air pollution removal capacity from green roofs have been conducted over the last two decades.

Approximately 80 papers were found in peer-reviewed journals in relation to the environmental benefits of green roofs including energy consumption reduction, urban heat island effect limiting, air pollution mitigation, water management improvement and ecological preservation inter alia. Nonetheless, the purpose of this paper is to find out how green roofs can improve air quality in the city of Barcelona. Therefore only 10 research papers focusing in air quality improvement were taken into consideration. That is to say, only research quantifying through specific models, in one hand, how much pollutants can a green roof absorb, and on the other hand, how much CO_2 is reduced from the urban air by green roofs[3]. Another criteria for selection was only to concentrate on those papers that are the most referenced and cited.

[3] Green roofs can help to reduce CO2 levels in the atmosphere in two ways. For instance, carbon is an important and one of the main components in plants, and it is naturally sequestered in plant tissues via photosynthesis and into the soil substrate via plant litter and root exudates. Second, they reduce energy consumption by insulating individual buildings, therefore mitigating the urban heat island, as previously mentioned. Maximum temperature reduction at street level, thanks to GRs can go up to 3ºC (Smith and Roebber, 2011).

Deustch et al. (2005) conducted a simulation study through a UFORE model in Washington, DC. According to the findings, installing green roofs on 20% of all green roof-ready buildings would eliminate the same amount of pollution as planting 17,000 trees. In terms of particular contaminants, Clark et al. (2005) calculated that installing green roofs on 20% of all industrial and commercial roof surfaces in Detroit, would eliminate over 889 metric tonnes of NO_2 per year. That is the equivalent to 13.4% of the total NO_2 expelled in Detroit's air in 2014 (EGLE, 2019). Directly above a green roof in Singapore, SO_2 and NO_2 levels were reduced by 37% and 21%, respectively (Tan and Sia, 2005). Similarly, Currie and Bass (2008) conducted a modelling study in Toronto, Canada, and found that 109 hectares of green roofs would eliminate almost 8 tons of air pollution per year. That is 5% of all Ontario's pollution during 2019 (ECCC, 2021). Yang et al. (2008) used a dry deposition model to estimate the effect of green roofs on Chicago air pollution. According to the findings, air contaminants removal were removed at a rate of 85 kg/ha in one year, with ozone accounting for 52% of the total, followed by NO_2 (27%), PM_{10} (14%), and SO_2 (7%). Speak et al. (2012) looked at the performance of four different vegetation scenarios in green roofs located in Manchester City Center buildings. Results showed a potential reduction of 2.3% of all Manchester's PM_{10} pollution in one year. Jayasooriya et al. (2017) observed a lowering of 930 kg of pollutants by green roofs in Victoria, Australia.

Green roofs have a lot of potential for CO_2 sequestration. Getter et al. (2009) performed measurements in Detroit to assess the efficiency of existing green roofs in terms of carbon sequestration. He stated that if all the rooftops in Detroit's metropolitan area were replaced with green roofs, 55.252 tonnes of carbon could be absorbed. Being that the volume equal to the emissions from about 10,000 cars. Li et al. (2010) investigated the effect of green roofs on CO_2 levels in Guangzhou. As compared to a normal rooftop environment, data showed a 9.3% reduction in CO_2 concentration in the green roof area. In addition, Moghbel and Salim (2017) conducted a field study in Tehran, Iran, to assess the efficacy of green roofs for CO_2 emission reduction. The GRs decreased the outside CO_2 concentration by 28 ppm less than a non-vegetated roof, according to the findings. The global average of atmospheric carbon dioxide in 2019 was 409.8 ppm (Lindsey, 2020). Looking at Moghbel's and Salim's (2017) results, it can be stated that the use of GRs could reduce 6.8% the global average of atmospheric CO_2.

Other relevant facts found in the literature review are that an extensive green roof of 19 m² will remove the same amount of contaminants as a medium-sized tree (Yang et al., 2008). Sailor (2008) developed a model to see how much CO_2 could the 1.1 km² rooftop area of the Michigan State University save if greened. He found out that they could forestall 3,640.2 tonnes of CO_2, being that the equivalent of eliminating 661 vehicles off the road every year (US EPA, 2005).

Something relevant to keep in mind is that all numbers mentioned above depend on climate conditions, type of green roof and its design. Nevertheless, green roofs have been around for over a century, and in recent decades, they have become one of the key elements of study in some urban areas. Several other scientific studies concentrate on important features like its cooling performance, productivity, and plant survival rates.

The studies described above demonstrate the potential advantages of using green rooftops to improve air quality. However, many elements of this mitigation measure are still unknown for many institutions. More research is needed to determine whether a green roof can be an effective way to improve air quality in cities. This study poses the following questions that will be addressed: Is there a way to quantify the level of air pollution removed after installing green roofs in a city? How much CO_2 would green rooftops absorb? Will the coverage by green roofs of 40 or 60% Barcelona’s suitable GR area take us closer to the Paris Agreement goals? What are the costs and economic implications of green roofs for public institutions, companies or private individuals? This paper will address those questions with a case study in Barcelona, Spain.

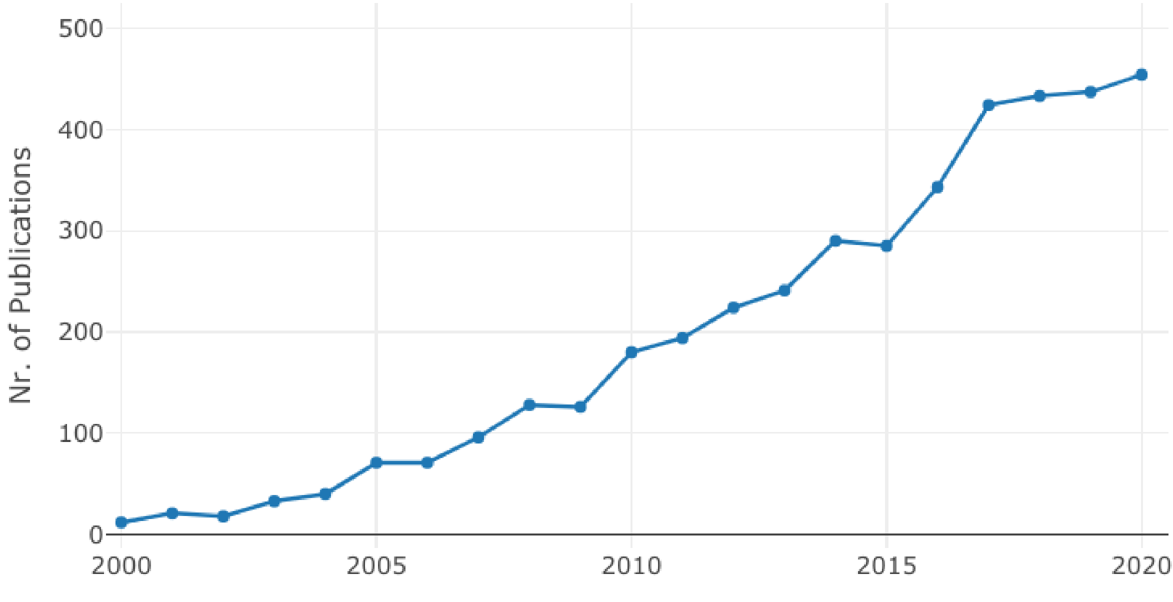
Quantifying the improvement in air quality caused by GR in the Spanish setting would thus give additional information for formulating policies and guidelines for future GR implementations. Such research will also improve public awareness of the more tangible and long-term advantages of GR.

1.4. Current Green Roof Panorama

Green roofs are vegetated areas composed mainly of plants that are normally grown on a specific substrate material on the roof of a building. Plant layer, soil media, drainage layer, and root barrier layer are among the basic layers found in GRs. The general consensus classifies GRs either as 'intensive' or 'extensive (Fig. 1.8). Intensive roofs are characterized by having a substrate layer greater than 15 cm. Therefore, allowing plants like ornamental lawn, flowers, demanding shrubs, bushes and trees to be planted. They also tend to have higher costs due to its regular demand of maintenance and the need for better structural design of the building to support the weight. In contrast, extensive roofs consist of substrate layers lower than 15 cm, where plants more drought-resistant like sedum plants, bulbs, wild flowers and succulents can be grown. In this case, less technical expertise is needed and the costs of maintenance and construction are much lower (EFB, 2021).

With their major environmental strengths, GRs have gotten a lot of attention in the last two decades. The number of publications around the topic are increasing each year.

Figure 1.8: Number of Publications with *'Green Roofs'* as a Keyword over the last two decades



Source: Self creation. Data extracted from: Scopus.com, 2021

In several countries like Switzerland, Canada, Germany, United States of America and Japan, green roofs are being required, recommended, and/or subsidized. (Bredari et al., 2014, Vijayaraghavan, 2016). For example Basel (Switzerland) is the city with the largest area of green roofs per capita in the world, with 5.71 m²/inhabitant. This has been achieved through initiatives supported by the City of Basel Council. The initiative started around 1996 promoting green roofs via investment programmes, which provided subsidies for green roof installation (20-40 CHF per m²). The programs were supported by the Energy Saving Fund, which receives 5% of all customer's energy bills in the region of Basel. In 2010 an amendment to the City of Basel's Building and Construction Law was passed. It states that all new and renovated flat roofs must be greened, as well as design guidelines for doing so. The initial costs of green roofs were about 100 CHF per m², now counting with the subsidies technology improvements, costs go down to about 23 CHF per m² (ZHAW & GRaBS, 2021). Another good example is the German city of Hamburg where 70% of all suitable flat rooftops are green rooftops. The Hamburg Ministry of Urban Development and Environment together with IFB Bank allocated a fund facilitating the greening of Hamburg's rooftops. The minimum surface area of a new green rooftop has to be of at least 20 m² to apply for the subsidy (hamburg.com, 2021). In the US and Canada the leading cities with the most planted GR area are Washington, DC and Toronto with 70.000 m² and 32.500 m² respectively (GRHC, 2019).

In 2019 the north-american non-profit industry association of Green Roofs for Healthy Cities conducted a study screening the top 10 metropolitan regions with GRs in the US and Canada. The total of these areas sum up to 289.190 m² with a corresponding sequestration of 120 metric tons of carbon each two years. This area equals almost 40 football fields and absorbs the CO_2 pollution of 26 typical passenger vehicles (EPA, 2018). Each german-speaking city mentioned above counts with about 100 hectares of GRs. That equals to 1 million m² each. Extrapolating some of the gathered data, it can be stated that Basel and Hamburg green roofs absorbed together a total of 415 metric tons of carbon each year. Being that the equivalent of eliminating 90 typical passenger vehicles of the roads each year. Nonetheless, the leading country with the most GR area is Germany with over 86 million m² (EFB, 2015).

The European Federation of Green Roofs & Walls is an active association that advocates and encourages the use of green roofs in their respective countries to help solve problems such as climate change, ecosystem services, green infrastructure, and a shortage of green space in the built environment. It counts with more than 350 small to medium companies from 16 european countries. Some of these enterprises were funded by the EU Commission. During 2015 the EFB screened 8 different associated countries and its green roofs industry. Results for that year show a total of € 382 million as yearly sales.

Furthermore, they predicted the European market for green roofs to reach € 6.8 billion as per 2017. On the other hand, they stated three different market barriers. These being the following, first most of European cities treat GRs as a relatively unimportant element of the built environment, second a financial barrier in the form of costs and lack of subsidies, and third an absence of innovation in the design of high-quality lightweight GR systems. Although being a small market, the EFB recognizes a huge potential, being London a good example with a market growth of 300% in only 7 years. This was achieved with adoption of favorable planning policies for the implementation of green roofs in city buildings. Considering that two-thirds of the European population (365 million people) live in urban areas, a need for green spaces is almost necessary. The EFB suggests that the GR industry should supply this necessity by providing at least 5 m² of GR per habitant. This future perspective would scale the industry to a market up to €62 billion worth (EFB, 2015).[4]

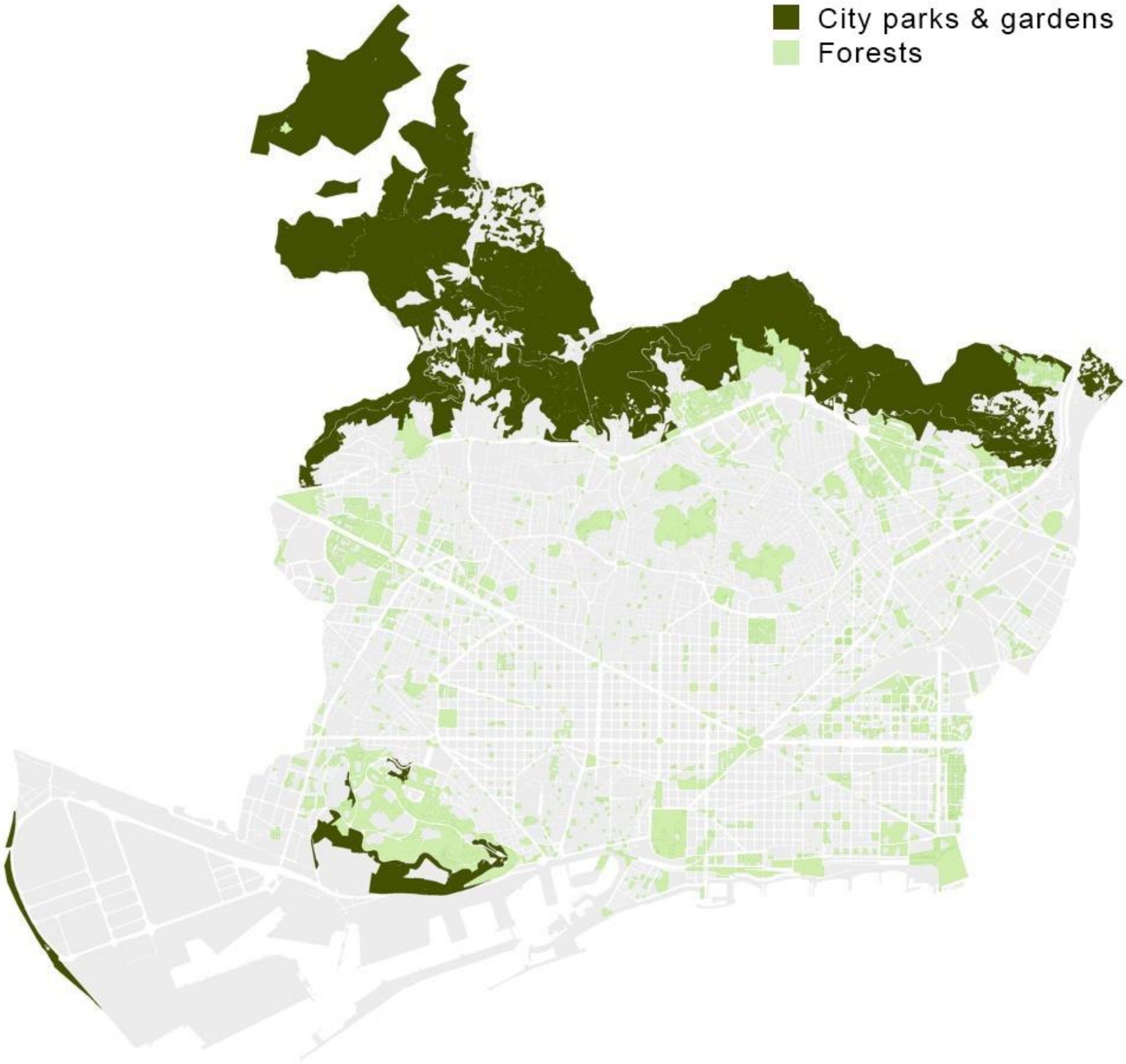
2. Study Site and Methods

This study focuses on Barcelona, Catalonia, which is located along the northeast coast of Spain by the Mediterranean Sea. The total area of the city is 101.9 square km. Barcelona is the second most populous city in Spain with a population of 1.6 million in 2020, and its metropolitan area ranks seventh in most populated areas in Europe with 4.9 million inhabitants (EC, 2019). As a highly dense and compact city, green space per capita is extremely restricted, with just 7 m²/inhabitant in the city center (17 m²/inhabitant when included the suburban park *Collserola)* (BCC, 2013), which is extremely low by European Union standards (26 m² per capita) (Kahlil, 2014). Similar populated European cities like Barcelona are Vienna or Hamburg. They have 95 and 114 m²/capita of green space respectively (Vienna City Administration, 2015; Cömertler, 2017).

According to the ASPB 35% of Barcelona's population is exposed above NO_2 legal levels and 100% is exposed above $PM_{2,5}$ established limits. In the city of Barcelona, 14% of the annual deaths can be attributed to urban air pollution (2.100 defunctions). Official research indicates that 22% of lung cancer deaths and 61% of childhood asthma annually registered in Barcelona, is caused by air contamination (ASPB, 2019).

[4] More up to date figures were not available during the creation of this study. The publishing of new industry figures from the EFB is due at the end of 2021.

Figure 2.1. Green space in Barcelona metropolitan area



Source: Urban Ecology Agency of Barcelona, 2010

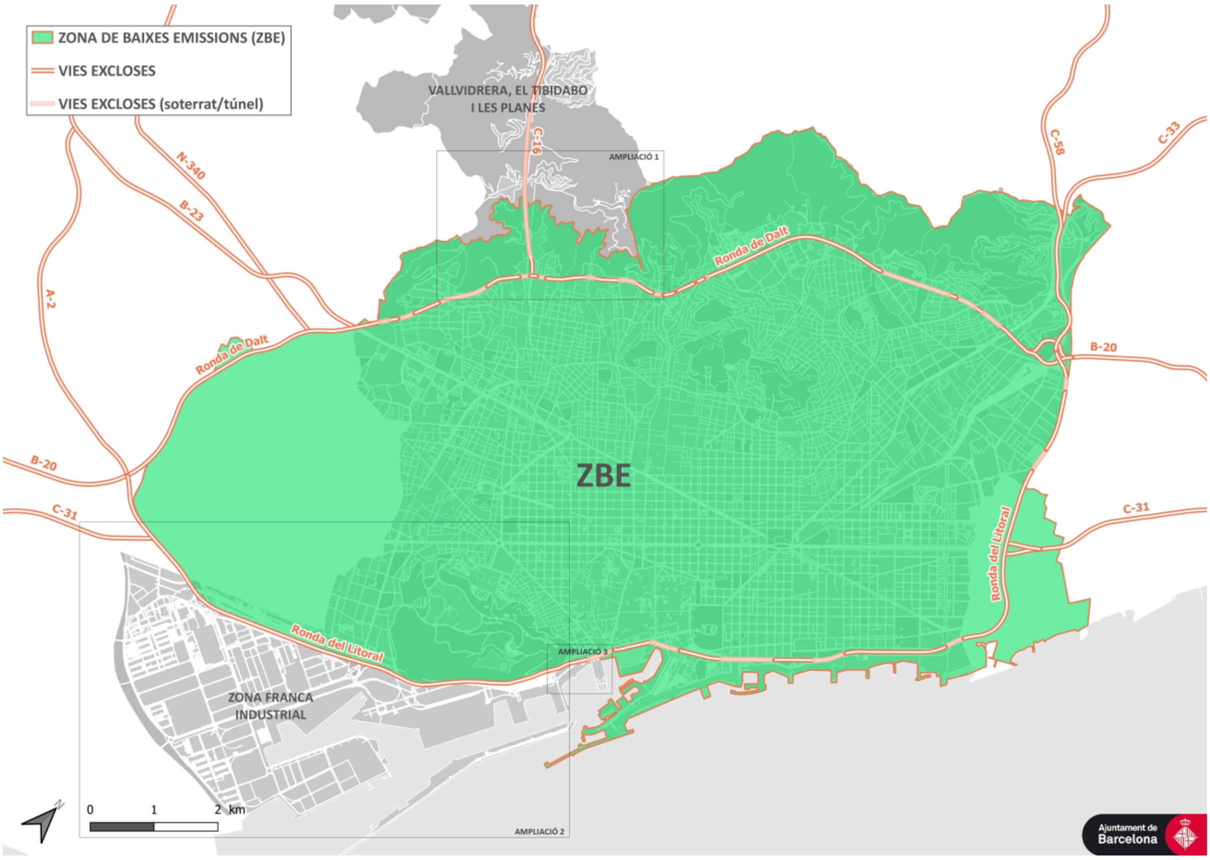
In 2020 the City Administration signed and activated Barcelona's Climate Emergency Plan. A plan in the form of 100 urgent measures to be applied until 2030. It is a clear response to work accordingly to the EU developed Paris Agreement during 2015. The BCC will invest over 500 million Euros to activate all these measures. Considering Barcelona as a compact city with a high residential density and a big deficit on green spaces, the Barcelona Climate Emergency Plan envisages actions to increase green areas in the city rooftops. Following a clear objective of improving the actual urban model and the environmental conditions of the city, the plan clearly states a developing of green roofs in the upcoming years (BCC, 2020).

Nonetheless, the recognition of Barcelona's air quality problem date back to November 2016, when the city government presented a pack of measures against the atmospheric contamination in Barcelona. With the clear objective of giving compliance to the WHO and EC recommendations to reduce air contamination indicators surpassing the limit levels established by European Laws, therefore protecting the health of Barcelona's inhabitants. The program includes structural measures in order to face high pollution episodes and actions impacting areas like the urban model, mobility, big infrastructures, delimitation of Low Emission Area it. al. On March 2017, the government administration linked and extended the plan to reduce in 15 years 30% of greenhouse gas emissions directly associated to transport (BCC, 2021).

These are the measures applied over the last four years having a direct diminishing effect on Barcelona's air pollution:

1. Establishment of a Low Emission Zone (ZBE in spanish)

Figure 2.2. Included area and excluded highways in the Low Emission Zone



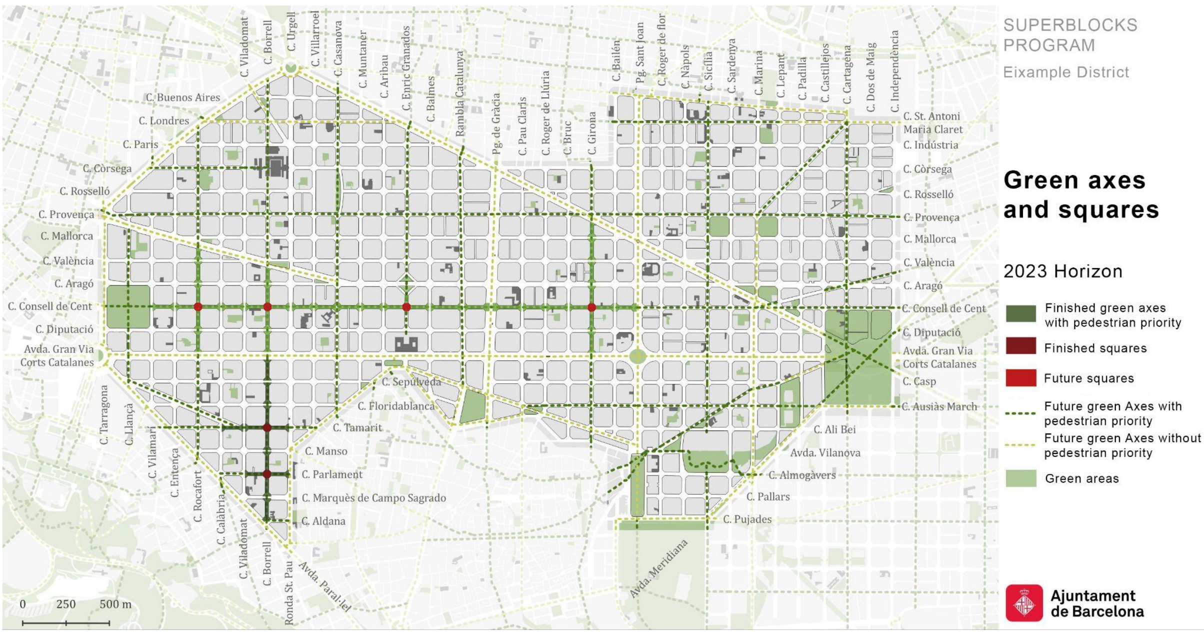
Source: Barcelona City Council, 2021

This area comprises 95 km² of Barcelona's urban center and surrounding agglomerations. The idea behind the ZBE is to restrict progressively the use of private vehicles with a high contamination rate. To make this effective Barcelona's Traffic Institution asks private vehicle owners to register online their vehicles in order to get an adhesive label proving the allowance to drive inside the zone. Since January 1st 2019, normal gas vehicles registered before the 2000, diesel vehicles registered before 2006 and motorbikes registered before 2004 are not allowed to drive inside this area only during high pollution episodes. From January 1, 2020 the prohibition extends from Monday to Friday from 7:00 am till 8:00 pm. Not having the required label can carry an economic sanction starting at €100 (BCC, 2021). In other European cities like London, Berlin and Paris, Low Emission Zones have been active since 2008, 2010 and 2015 respectively. Another palliative measure against high pollution episodes is the application of higher parking fees to highly polluting vehicles or even parking prohibition.

2. Changes in Barcelona's urban model

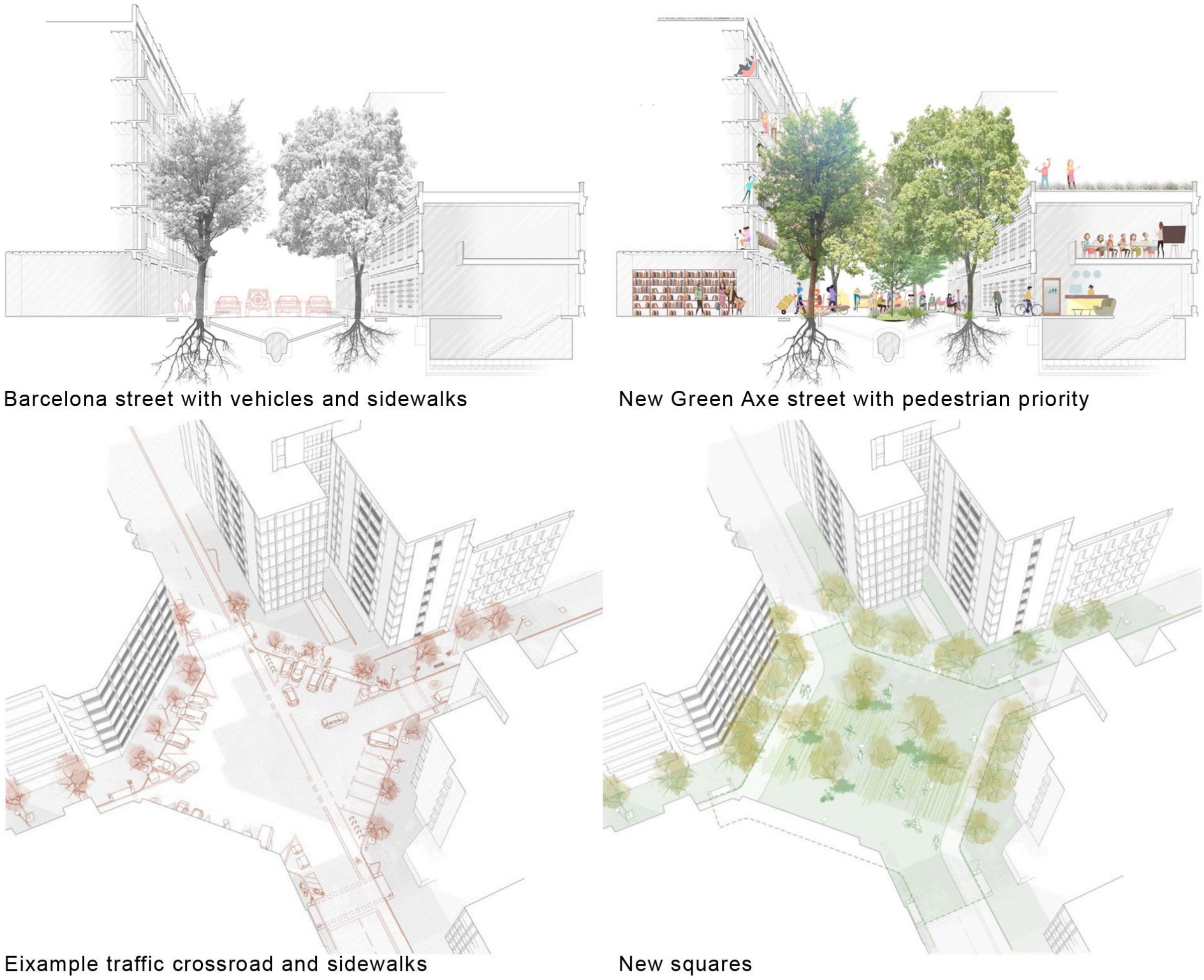
   New space for pedestrians eliminating driving streets and blocks, creating the so-called *superilles* (superislands or superblocks in Catalan) in the *Eixample* district. Till the date, two superblocks near St. Antoni Market have been executed and are free for pedestrians to walk through. Construction works started in early 2017 and were finished in late 2019.

Figure 2.3. Eixample District Superblocks Program for 2023



Source: Barcelona City Council, 2021

Figure 2.4. A before & after architectural vision of Barcelona's Green Axes and Squares



Source: Barcelona City Council, 2021

Apart from this, the changes in Barcelona's urban model include the closing of major streets and avenues to vehicles every Saturday and Sunday from 9:00am till 9:00pm. During 2020 streets like *Aragó, Gran de Gràcia, Creu Coberta* and *Via Laietana* remained each weekend closed to vehicles. Now only *Creu Coberta* and *Gran de Gràcia* are still closed to motorized traffic during the weekend. Summing up a total of 3.1 km of walkable streets. Furthermore, a total of 10.5 km of streets and avenues have experienced an amplification of its sidewalk. Most of them in the form of colored asphalted areas.

Figure 2.5. Streets where pedestrian sidewalks zones have been amplified

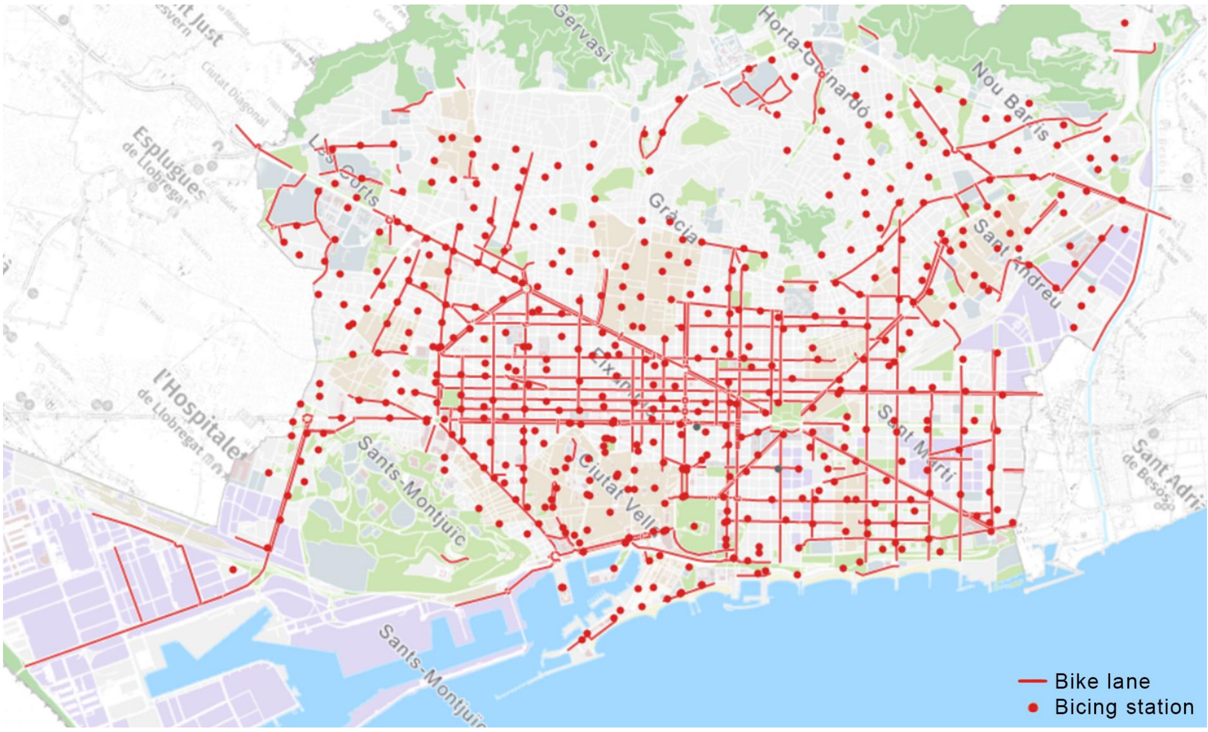
Source: Map (Barcelona City Council), left photograph (Construala) & right photograph (metropoliabierta.com), 2021

3. Foment the use of public transport

   An optimization of Barcelona's bus lines has taken place since 2012. The objective was to update and give structure to the old bus network. From the old 43 lines, 30 have preserved its original route, 13 lines were modified and 63 new lines were added to the net. The total lines today sum up to 103 bus lines with 30 km of new bus lanes.

Bicing, Barcelona's public bike sharing system was founded in 2007 with 97 docking stations. As per 2021 the public service has 517 docking stations. The total extension of bike lanes also experienced a significant growth over 5 years. Going from 120 km in 2015 to 231 km of bike lanes in 2020, representing a growth of 92.5% (BCC, 2021)

Figure 2.6. Bike lanes and Bicing docking stations in Barcelona



Source: Barcelona City Council, 2021

4. Foment the use of low polluting vehicles

Discharging high polluting vehicles[5] will allow owners a free public transport card valid for three years since the discharging date (TMB, 2021). The city has two fully electric public transport buses and plans to incorporate seven more. Moreover Barcelona accounts for the registration of 15% of all spanish electric vehicles. Owners of electric vehicles living in Barcelona can save annually 75% of the road tax and can park for free in public parking areas. The city has over 300 electric vehicle charging points. Furthermore the Catalan Government has established a tax against the CO_2 emissions of vehicles. With a range of 0.7 - 1.4 € per gram of CO_2 expelled

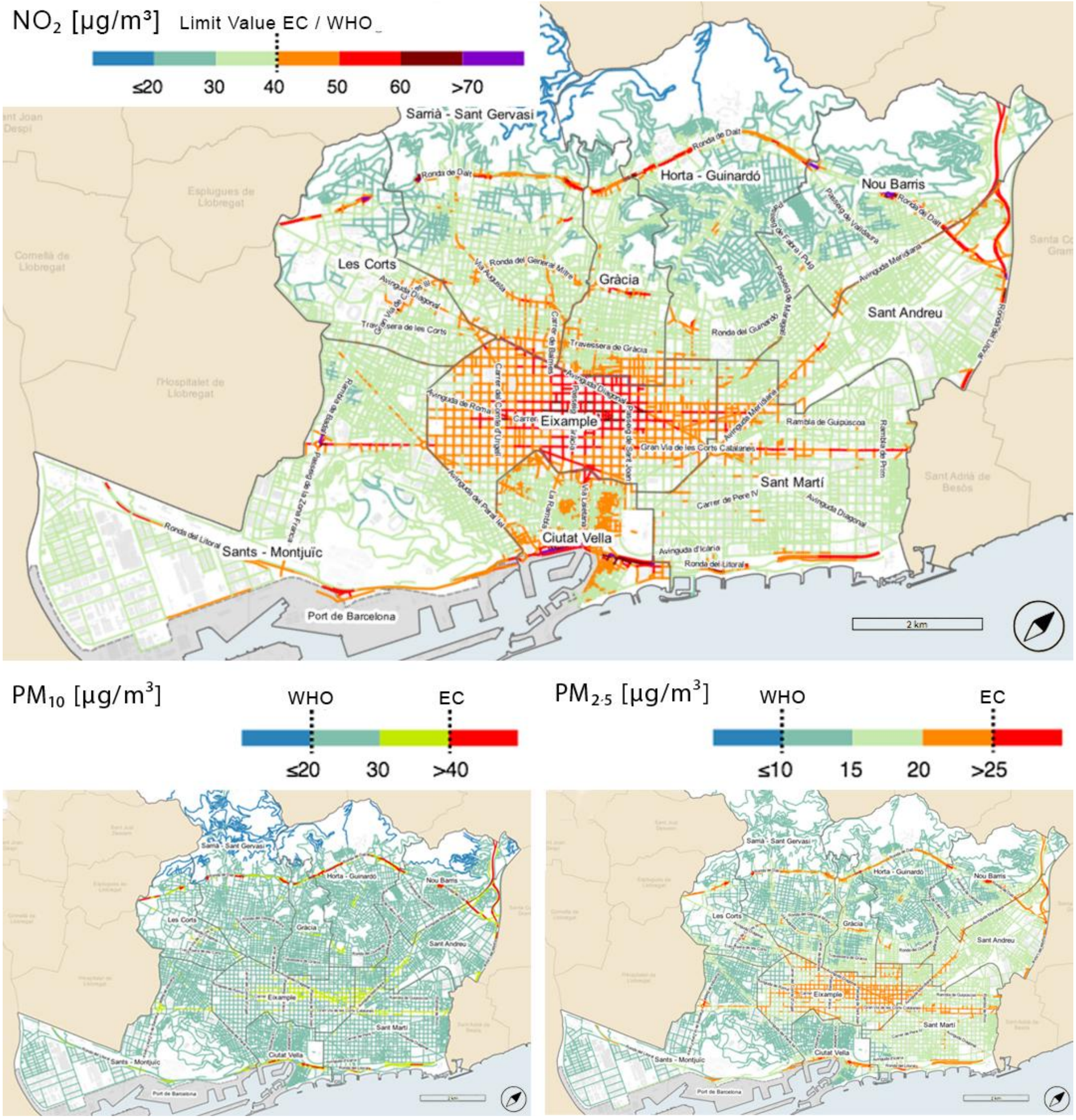
[5] Diesel vehicles registered before 2006, gas vehicles registered before 2000 or motorbikes registered before 2004.

each kilometer. The tax range varies proportionally to how much CO_2 the vehicle emits to the atmosphere (BBC, 2021). Additionally 12 private companies offer in Barcelona's urban center an e-scooter sharing service with approximately a total fleet of 7,000 e-scooters (Guerrero, 2020).

5. Specific measures during High Pollution Episodes
   Barcelona inhabitants are being informed of these Episodes through traffic panels in. al. Health centers and high vulnerability groups are also warned of the situation. During the Episodes there is the possibility of buying a two-way public transport ticket with a 10% price reduction. The Council also irrigates with phreatic water streets, squares and parks in order to reduce high concentrations of PM_{10} and $PM_{2,5}$. Construction works with high particle emissions are also stopped during these periods (BCC, 2021).

The Barcelona City Council offers an interactive visualization of the pollution concentration found in the streets. These pollution levels are shown in the form of an annual average indicators. Although the information gives an accurate statistical vision of Barcelona's pollution, something to keep in mind is that on some specific days contamination levels can be much higher than shown in these maps and that the EC allows some exceedances during the year on some pollutants.

Figure 2.7. Barcelona city's air pollution during 2019

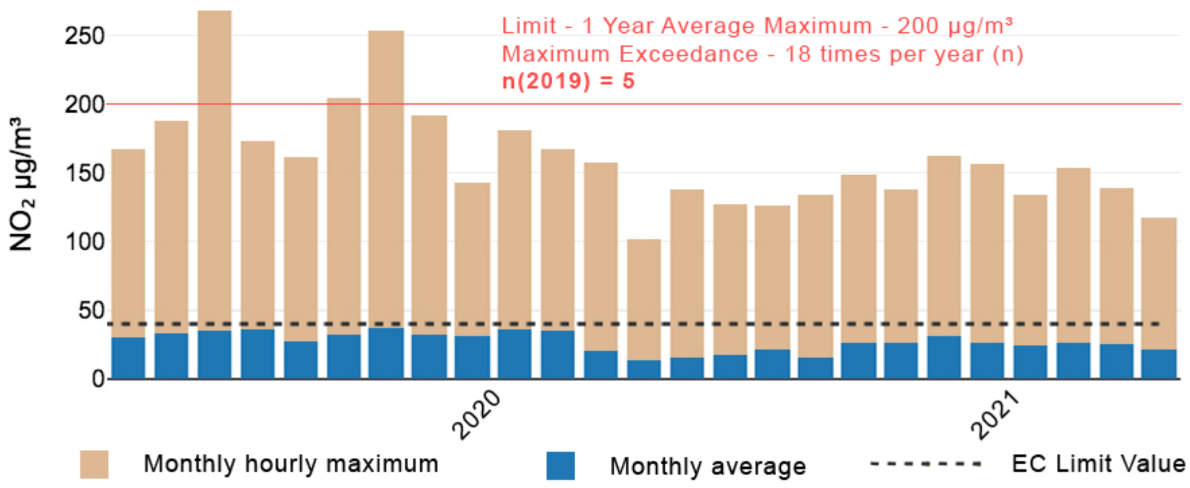


Data source: Barcelona City Council, 2019

European Commission NO_2 levels are surpassed in a major part of the city center during 2019. Including 12 critical areas where levels are over 65 µg/m³. PM_{10} levels are under EC levels in almost all parts of the city, but still over WHO recommended levels. About 15 critical traffic points can be found surpassing EC PM_{10} limit levels. On the other hand, $PM_{2,5}$ levels are still worrying in big part of the Eixample district and some small critical areas of all the rest of Barcelona districts.

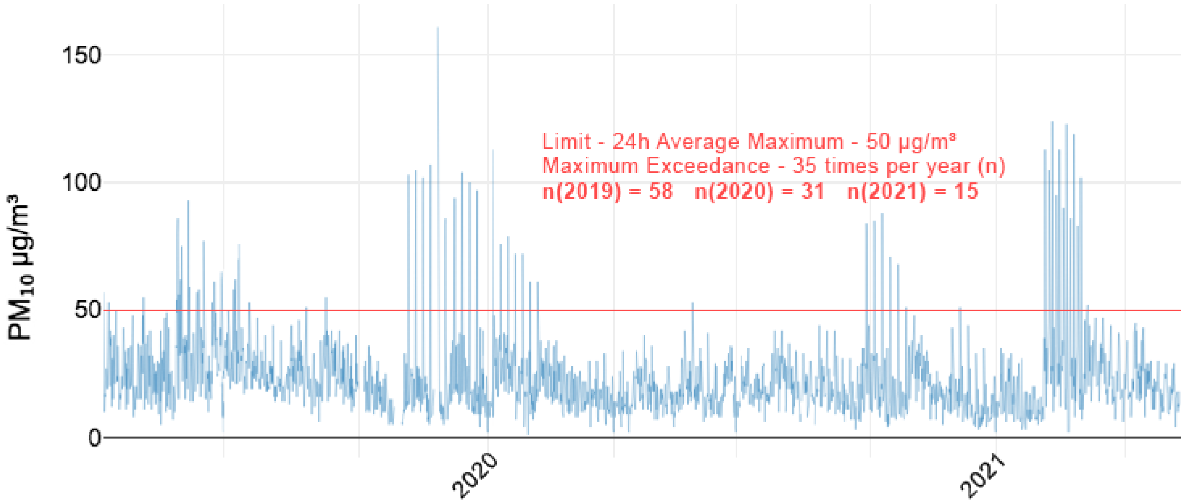
Furthermore the City Council also offers publicly available data of 7 different air measure stations located in the urban center. The data is collected hourly since June 2018. Nonetheless, the measuring system changed starting from February 2019, causing a gap of 2 months without air pollution data due to maintenance works (BCC, 2021). On that account, this study can only analyze data starting from April 2019 and take only 2020 as a complete year of air pollution data. The first analysis stated that pollutant levels of SO_2, O_3 and CO were under legal limits. Nonetheless NO_2 and PM_{10} surpas in some cases the EU established legal limits during the data time period. $PM_{2,5}$ data was not available. For the second analysis (NO_2 and PM_{10}) a total of n = 255,024 air measurements were screened, of which 7,909 showed no result, therefore offering an accuracy level of 97%.

Figure 2.8. NO_2 hourly maximum and monthly average levels in Barcelona's air measurement stations from April 2019 to April 2021



Source: Self creation. Data extracted from: opendata-ajuntament.barcelona.cat, 2021

Figure 2.9. PM_{10} 24h average levels in Barcelona's air measurement stations from April 2019 to April 2021



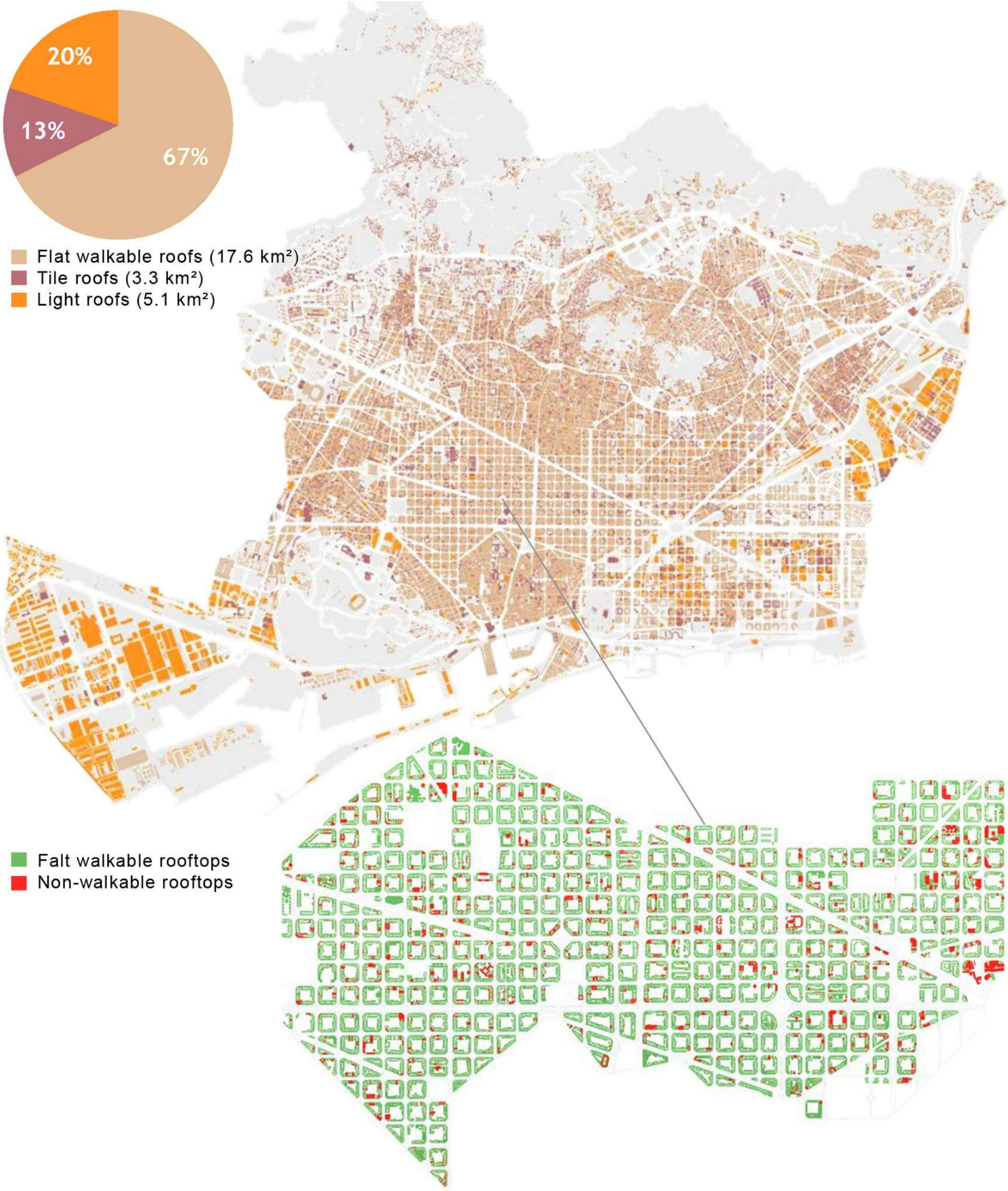
Source: Self creation. Data extracted from: opendata-ajuntament.barcelona.cat, 2021

Only in nine months 58 exceedances were reached during 2019. Although the levels of the last year are under legal limits, hourly maximum values are still worrying and health threatening. Whilst in only 4 months 15 exceedances have been accumulated during 2021. If this trend continues, by the end of the year, 45 exceedances could be reached and the legal limit would be surpassed.

2.1. Green Roofs in Barcelona

During 2014 and 2015 a study was published regarding green roofs in Barcelona. It was a study conducted mainly by a spanish public institution, in this case the Urban Planning Department of the City Council together with two important architecture and urbanism companies. The main goal of the publication was to inform the general public that green roofs can help Barcelona be more sustainable and fight against climate change. It exposes the well-known ecological and social benefits of green roofs, but very few words reference Barcelona's air pollution problem and how green roofs can mitigate it. The document also indicates that the Council will offer subsidies to all projects related to green roofs, covering from 25% to 50% of the total cost with a limit amount of €60,000 (BCC, 2015).

Figure 2.10. Roof typology in Barcelona's metropolitan area



Source: Espinet/Ubach Architects – Study Ramon Folch & Associates, 2010

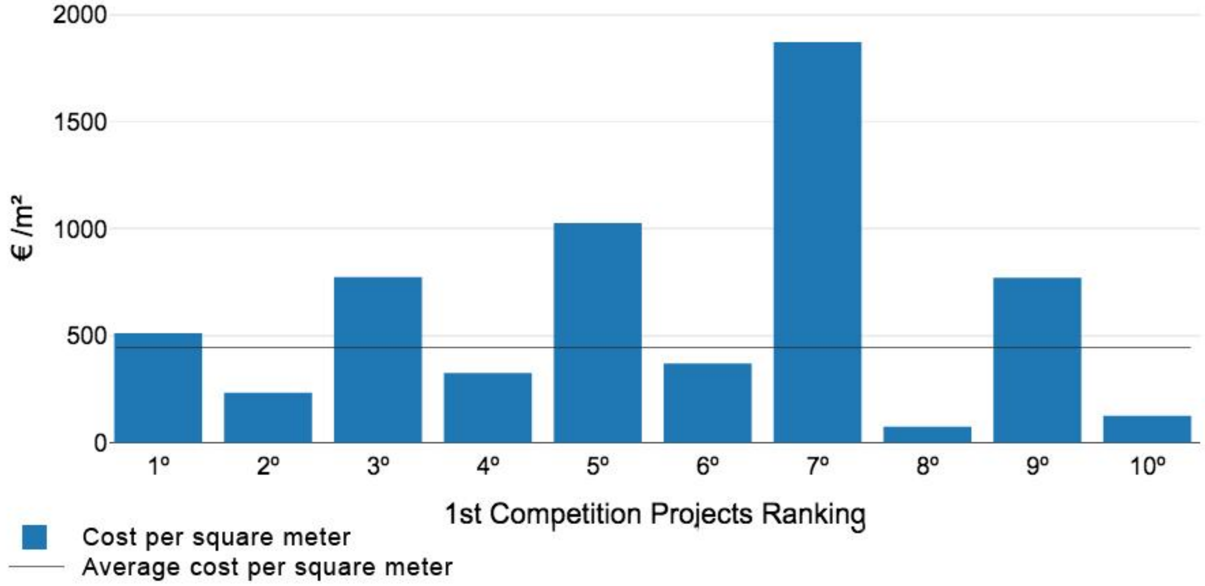
Four other studies published by local and international research institutes and universities have been conducted in the last three years. These studies measured the yearly performance and success of green roofs in the area of Barcelona with its Mediterranean climate conditions. Vestrella et. al. looked at the hydrological performance of green roofs with three local plants and different watering scenarios. Gilabert et. al. found out that green roofs in Barcelona can reduce on average 1.3 ºC the nearby temperature and a maximum of 4.7 ºC respectively. Langemeyer et. al. and Zambrano - Prado et. al. looked more in depth at the different opportunities and barriers for the integration of green roofs as an ecosystem service for Barcelona metropolitan area.

Walkable rooftops represent 67% of all Barcelona rooftops. Being that a potentially green roof area of 17.6 km² (Espinet/Ubach Architects – Study Ramon Folch & Associates, 2010). By late 2014 Barcelona had approximately 115 GRs, according to the Municipal Urban Ecology Agency about 4,000 m² (BCC, 2014). Two open green roof projects competitions have been completed till the date. The competitions were held in 2017 and 2020 respectively and offered to the 10 winning projects a funding of 75% of the costs with a limit of €100,000 per GR project. The competition funding was provided by the BCC in form of public subsidies.

Figure 2.11. Two winning projects in the 1st public competition

Source: Barcelona City Council, 2017

Figure 2.12. Cost per square meter of each winning project in the 2017 competition and average cost per sqm



Source: Self creation. Data extracted from: BCC, 2017

The two competitions added twenty new GRs with a total of 11,693 m² of green roof area. Eight other GR projects were constructed after 2015 summing up an area of 9,530 m². The *Reina Sofia Hotel* GR and Barcelona's Natural Science Museum GR stand out as the largest green roofs projects. Barcelona stands then with a total area of 25,223 m² of GRs. However, this represents only a small portion (~0.2%) of the city's GR expansion potential.

€4,950,542 is how much the 20 competition winning GRs projects cost. Counting an average cost of €445 per square meter, Barcelona's green roof total area is valued at €10,971,392. If only 40% of Barcelona's potential GR area would be built, the total value would be around 2 billion Euros. This would potentially lead Barcelona to a favorable position in the European green roof EFB market prediction, with about 30% of the market size (EFB, 2015).

2.2. Removal of air pollution by green roofs in different scenarios

Dry deposition models are one of the most extensively utilized methodologies for assessing GR's pollution mitigation capacity (Yang et al., 2008). In numerous case studies, models such as the Urban Forest Effects Model (UFORE), which employs dry deposition modeling techniques, were employed to estimate the reduction in air pollution caused by GRs. i-Tree Eco was recently released as an improved version of UFORE (Martin, 2011, Hirabayashi et al., 2012). The i-Tree Eco is a peer reviewed open-source software developed by the United States Forest Service Research. This was first utilized in multiple cities in the United States to evaluate the increase in air quality as well as various ecological services provided by GR (Nowak and Crane, 2000, Hirabayashi et al., 2012).

Although i-Tree Eco's primary role is to examine the air quality improvement of urban forests with trees, it has also been used to simulate the air quality improvement advantages of GR. Currie and Bass (2008) utilized the i-Tree Eco model to examine how green roofs and green walls improve air quality in Canada. Green roofs were simulated in this study by replacing the research area's roofs with appropriate plant species. Furthermore, Deutsch et al. (2005) investigated the improvement of air quality by green roofs in Washington, DC, by replacing the roof areas of Washington with various percentages of plant species to replicate green roofs. Based on the kind of vegetation and its structure, the i-Tree Eco program simulates air pollution removal. As a result, i-Tree Eco can simulate the removal of air pollutants by green roofs and green walls for a specific region by modifying the species and form of vegetation employed. The Catalan Gardening and Landscape Foundation offers a collection of plant species that might be suited for extensive green roofs in various temperature zones (NTJ 11C, 2012). i-Tree Eco may be used to mimic the air quality improvement through green roofs for the current case study location by replacing the roof regions with these recommended species.

In this study, the area for the i-Tree Eco simulation will be only the area of walkable flat rooftops existing in Barcelona. According to the research done by Espinet & Ubach Architects together with Ramon Folch & Associates, this area equals to 17.6 km2. From the Catalan Gardening and Landscape Foundation collection only plants suitable for extensive roofs in a Mediterranean coastal climate and full sun exposure were selected. Which turned out to be 50 out of 155 plants from the list with an average height of 24.7 cm. The maximum and minimum height of the 50 plants are 80 and 5 cm respectively.

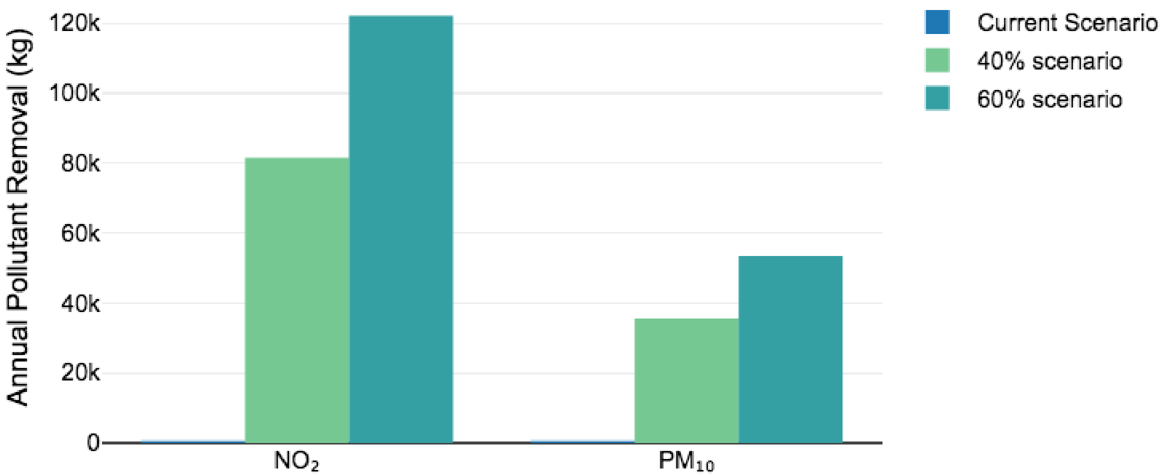
Using the data of the different GRs projects screened for this study, an averaged proportion of green area vs. rooftop area can be extracted. 63.2% is the average green area in a GR project. This ratio represents how much area tends to be planted usually in

Barcelona's green roofs. Calculations on how much pollution will be absorbed, will be more accurate using this ratio. Finally, two different scenarios will be observed and compared to the one existing. Two where 40% and 60% of the suitable rooftop area will be covered by extensive GRs respectively. The pollution data used for the estimations, corresponds to 2020, since it is the only available data of a full year. A more detailed description of the calculations and algorithms used for the estimation of air pollution removal through dry deposition models used by softwares like i-Tree Eco can be found in Yang et. al. (2008) and Jayasooriya et. al. (2017).

3. Results

Figure 3.1. shows the annual air pollution removal of extensive green roofs in two new scenarios in comparison with the baseline scenario for the study area. The new scenario where 40% of the available area is covered by extensive GRs, would provide a removal of 81,469 kg of NO_2 and 35,587 kg of PM_{10} annually. Proportionally, a potential scenario where 60% of the available area is covered by extensive GRs, 1.2 metric tonnes of NO_2 and 53,380 kg of PM_{10} would be removed. Whereas with the existing GR scenario only 462 kg of NO2 and 202 kg of PM10 are being removed yearly.

Figure 3.1. Comparison of annual air pollutant removal of extensive GRs in two different scenarios with the current scenario

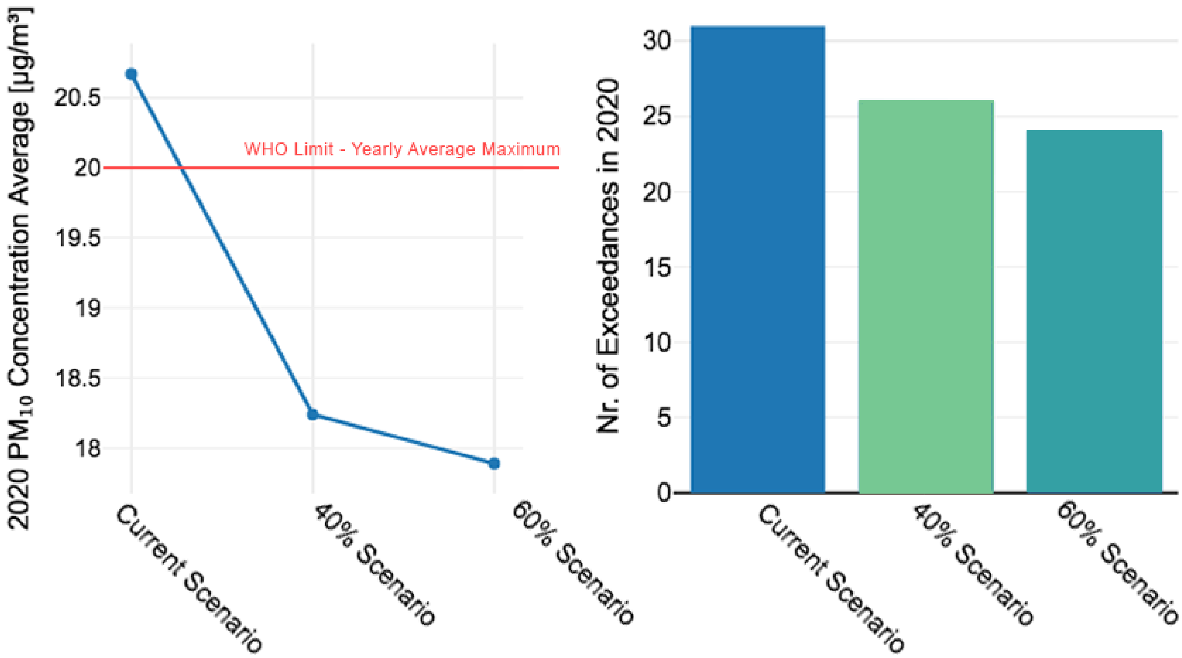


Source: Self creation. Data extracted from: Dry Deposition Modelling by i-Tree Eco Software, 2021

Figure 3.2. shows how the two different alternative scenarios (40 and 60%) can diminish the annual concentration average of PM_{10} and reduce simultaneously the number of

exceedances during one year. Covering during 2020 a 40% of Barcelona's available flat rooftop area with extensive GRs would have lowered the annual average of PM_{10} by 11.7% and the number of exceedances by 16.1%. On the other hand, the 60% scenario would have brought a reduction of 13.4% of PM_{10} levels and a 22.5% in the number of exceedances during 2020.

Figure 3.2. Comparison of annual concentration average and number of exceedances of PM_{10} for the studied scenarios during 2020



Source: Self creation. Data extracted from: i-Tree Eco Software and opendata-ajuntament.barcelona.cat, 2021

4. Discussion

Measures taken by local institutions (Section 2.1.) seem to partly fulfill their objectives. Moreover, as mentioned in the Introduction, $PM_{2,5}$ health effects are worse than PM_{10} effects and the 2019 map shows health-threatening concentration of this pollutant. Yet no hourly data about $PM_{2,5}$ concentrations is being openly published. Following the WHO and EU policies, Barcelona's public institutions should start measuring and tracking this particular pollutant. Even in the European Union, where PM concentrations in many cities meet guideline levels, it is estimated that due to PM exposure from human sources, average life expectancy is 8.6 months lower than it would otherwise be (WHO, 2018).

Officially reported data about Barcelona's CO_2 air concentration was not found for this study. Nonetheless, important meteorological stations around the world reported last year a CO_2 concentration of about 419 ppm. The Mauna Loa Observatory (Hawaii, US), is a global reference in terms of atmospheric CO2 measuring. In April 2021 it registered an historical record of 421.21 ppm of CO_2 (NOAA, 2021). Putting this in a future context with the Paris Agreement in mind, to reach a temperature increase of +2ºC by 2050, atmospheric CO_2 concentration should be only 450 ppm. Reaching 600 ppm of CO_2 would lead to an increment of +3ºC of the global temperature. An even more pessimistic projection would be an increase of +4ºC with 800 CO_2 ppm. In an overpopulated world where humans would not change their behaviour habits, 1,000 ppm of CO_2 would lead our global temperature to rise 5ºC extra. Going back to the actual CO_2 atmospheric concentration the monthly average values registered in Mauna Loa for April 2020 is 416.45 ppm and for April 2021 is 419.05 ppm. There is an increment of 2.6 ppm. Keeping this atmospheric CO_2 levels growth rate, by 2050 the global CO_2 levels would be around 494 ppm of CO_2 and by 2100 about 624 ppm, by then the global temperature would go beyond + 3ºC hotter. In this possible near future the Paris Agreement recommendations would not be met. That is why more and more different institutions and the general public around the world talk about 'climate emergency' or even 'climate crisis'. An urgent change of behaviour in our society and an imminent reduction of fossil fuel consumption is required. That not being the case, we will have to get used to live on a planet with a totally different climate from the one we are used to. In a review study, results show green roofs can uptake co2 in a range varying from 0.31 kg/m2 to 7.11 kg/m2 of CO_2 per year. Revealing the potential of GRs as a climate mitigation strategy by demonstrating their capacity to reduce CO_2 emissions in both direct and indirect ways, green roof plants photosynthesis and building energy consumptions savings (Shafique et. al., 2019). If direct and indirect benefits are evaluated in the mid and long term, our findings through the literature review show that GRs might play a significant role in lowering carbon emissions in the Barcelona urban environment.

It is estimated that Barcelona has about 28 km² of green space (BCC, 2013). With the proposed 60% extensive green roof scenario, that area would increase to 45 km². Raising the available green space per capita from 17 m² to almost 28 m², taking Barcelona to the compliance of European Union recommendations (26 m²/per capita). The average price of the screened GRs is about €445 /m² for the cost of installation. Although a small proportion of the existing GRs in Barcelona was analyzed, it is still worrying how high the cost per square meter is if compared with other European cities. Despite their high cost, there are various reasons why green roofs are a feasible air pollution mitigation option. A green roof's high initial installation costs can be compensated by its long-term advantages. Its construction and maintenance costs can be decreased if the industry is standardized and a full system for green roof manufacturing, distribution, and installation is established. Furthermore, unlike tree planting programs, which require land to be set aside and are less expensive, green roofs do not require land and are constructed on rooftops. This is a crucial aspect in high-density metropolitan areas.

5. Conclusion

Air pollution in metropolitan areas is a significant hazard to human health. As the world population expands and becomes more congested in metropolitan regions, new concepts and tactics are needed to help preserve clean air that is safe for everyone to breathe. This research looked at an innovative approach to air pollution control: extensive green roofs. Through a first analysis of the official online available data, health-threatening pollutants were screened to check its compliance with the legal established limits. By using a dry-deposition model (i-Tree Eco software), the non-complying air pollutants removed by three different green roofs scenarios in Barcelona were quantified. The results revealed that extensive green roofs may remove a significant quantity of pollutant from the air in Barcelona. Because of its high expense, the green roof cannot yet be employed as a stand-alone technique in air pollution mitigation. However, a thorough examination of its environmental advantages reveals that it might be a viable solution for reducing air pollution.

In 2020, due to the COVID-19 pandemic, spanish government ordered a 4 months (March to June) lockdown. Thereby reducing the urban transport to its minimum. This had consequently a direct lowering effect on air pollution levels for that time period. Reflecting on 2019 and 2021 air pollution data, the lockdown events probably maintained the 2020 levels under the EU legal spot. Therefore, in future research, there is a high need to evaluate Barcelona's GRs performance over a year where no lockdowns occur or where no monthly data is missing like in 2019.

A key takeaway is that, in the urban setting, climate change adaptation and mitigation can coexist; these examples show how adaptation can be fueled by energy-saving and climate-change mitigation behavior. In order to avoid maladaptation, certain possibilities for using current and ongoing urban and infrastructure improvements guided by other agendas for the purposes of adaptation should be pursued and maximized. Green roofs are a great example of how this can be done.

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