Greening of European Cities: Social Benefits of Urban Nature for Urban Air Quality

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Summary: While current climate and environmental efforts are mostly focused on the necessary and urgent CO2 emissions cuts, energy transition and climate adaptation, other not least pressing issues such as *air quality* start reaching the political agenda (European Commission, 2019). In this paper, we address air pollution from the *social welfare perspective* and bring together two strings of literature on the productivity of green urban infrastructure for ambient air quality and the monetisation of air quality improvements. Based on the *EU air quality data* by country and city, we identify those regions, which would benefit most from improved urban green infrastructure to improve air quality performance in Europe. We review a set of academic literature on the impact of urban green combating urban air pollution, and provide a synthesis review of social externality costs connected to urban air pollution. We extrapolate, in a stylized manner, the effect of increasing urban vegetation throughout the EU and in a selection of EU cities. Our estimates show that additional 1m2 of green cover throughout the EU cities would lead to 65,9 mln EUR of benefit per year, split about equally between the benefits of improved air quality and carbon sequestration, equivalent to 976 euros per ha per year for air pollutants and 1024 euros per ha per year for carbon abatement.

Keywords: air pollutants, green infrastructure, social cost of carbon, benefits of urban green; alue estimation

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1. Introduction

Nowadays, most of the points on political agendas regarding climate change concern the reduction of carbon dioxide (CO2) emissions. This is absolutely necessary, as increasing CO2 emissions have irreversible effects on the planet. Some of those include shortages of food and water, unpredictable weather conditions, droughts, loss of biodiversity resulting in deaths of millions of people and deepening inequality[1]. Additionally, carbon dioxide also poses a number of health risks on people, depending on the level of concentration of CO2 they are exposed to. Therefore, meeting CO2 emissions targets is crucial, however, not sufficient. Other pollutants, such as nitrogen oxides, sulphur dioxide and particulate matter have even stronger impact on the global greenhouse-effect, as well as add major adverse health effects on humans. Air quality issue, though well-recognised, does not often receive due attention.

The adverse health effects resulting from increased air pollution are widely recognized by most of the world's population. Every year, approximately 3.7 million people die prematurely due to air pollution worldwide[2]. Moreover, exposure to air pollution increases a person's risk of catching a disease such as stroke, heart disease, lung cancer and chronic bronchitis, with heart disease and stroke being the most common reasons for premature death[3]. This incidence on health creates a major impact on economy. Perhaps the most obvious one is that the increase in the number of sick people caused by air pollution increases the medical costs[4]. Furthermore, air pollution also reduces incomes in the countries, by causing a loss of productive labor. Air pollution can also halt productivity in other ways, e.g. by stunting plant growth and reducing the productivity of agriculture[5].

Reducing pollutant emissions at the source is arguably the most direct way to improve air quality[6], however, authorities around the world have struggled

1 STERN, N. We must reduce greenhouse gas emissions to net zero or face more floods. *The Guardian.* 2018.

2 World Health Organisation. Ambient (outdoor) air quality and health. fact sheet no 313. *EU Commission, Mobility and Transport*. 2014. [online] <http://www.who.int/mediacentre/factsheets/fs313/en/>, accessed on January 14, 2020.

3 World Bank. The cost of air pollution: strengthening the economic case for action. *Washington: World Bank Group*, The World Bank and Institute for Health Metrics and Evaluation University of Washington, Seattle. 2016, Report nr. 108141.

4 RODRÍGUEZ, M.C., DUPONT-COURTADE, L., OUESLATI, W. Air pollution and urban structure linkages: Evidence from European cities. *Renewable and Sustainable Energy Reviews,* 2016, vol. 53, pp. 1–9.

5 WORLD BANK, 2016.

6 KUMAR, P., DRUCKMAN, A., GALLAGHER, J., GATERSLEBEN, B., ALLISON, S., EISENMAN, T.S., HOANG, U., HAMA, S., TIWARI, A., SHARMA, A. The nexus between

to meet the air quality standards through emission control strategies alone. A possible urban planning solution for this problem could be expanded green infrastructure in the built environment which has the potential to improve air quality along with enhancing the sustainability of cities for growing urban populations and climate resilience[7]. Such nature-based solutions may include vegetation barriers, street parks, green walls, green roofs and street trees. These tools of urban green infrastructure can also provide benefits such as potential reduction in energy consumption[8], noise pollution[9], mental and physical health benefits[10] and climate change mitigation[11].

While benefits of green infrastructure belong to non-market goods and services that are not directly priced, they still hold value to society and therefore need to be made explicit. While disputable, failure to monetise such benefits of environmental goods leads to suboptimal decisions such as underprovision of urban infrastructure and its multiple positive effects[12]. To date, multiple methods are available and applied in environmental economics to estimate value of untraded environmental goods and services. Similarly, there has been a lot of research done regarding the absorption abilities of air pollutants by various types of green infrastructure. However, there is very limited information available on how can the reduction in air pollutants' concentrations caused by urban green space be translated into the monetary value of increased social welfare due to better air quality. Thus, in this paper, these two strings of literature are uniquely

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air pollution, green infrastructure and human health. *Environment international*, 2019*,* vol. 133, pp. 105–181.

7 IRGA, P., BURCHETT, M., TORPY, F. Does urban forestry have a quantitative effect on ambient air quality in an urban environment? *Atmospheric Environment,* 2015, vol. 120, pp. 173–181.

8 BERARDI, U., GHAFFARIANHOSEINI, A., GHAFFARIANHOSEINI, A. State-of-the-art analysis of the environmental benefits of green roofs. *Applied Energy,* 2014, vol. 115, pp. 411–428.
PÉREZ, G., COMA, J., MARTORELL, I., CABEZA, L.F. Vertical Greenery Systems (VGS) for energy saving in buildings: A review. *Renewable and Sustainable Energy Reviews,* 2014, vol. 39, pp. 139–165.

9 BERARDI, U., GHAFFARIANHOSEINI, A., GHAFFARIANHOSEINI, A. State-of-the-art analysis of the environmental benefits of green roofs. *Applied Energy,* 2014, vol. 115, pp. 411–428.
COHEN, P., POTCHTER, O., SCHNELL, I. The impact of an urban park on air pollution and noise levels in the Mediterranean city of Tel-Aviv, Israel. *Environmental Pollution,* 2014, vol. 195, pp. 73–83.

10 LOVELL, R., DEPLEDGE, M., MAXWELL, S. Health and the natural environment: A review of evidence, policy, practice and opportunities for the future, 2018.

11 MATTHEWS, T., LO, A.Y., BYRNE, J.A. Reconceptualizing green infrastructure for climate change adaptation: Barriers to adoption and drivers for uptake by spatial planners. *Landscape and Urban Planning,* 2015, vol. 138, pp. 155–163.

12 BOCKARJOVA, M., BOTZEN, W.J.W., KOETSE, M.J. Economic valuation of green and blue nature in cities: A meta-analysis. *Ecological Economics,* 2020, vol. 169, pp. 106–480.

brought together. In particular, the review of economic literature on the value of social externality costs connected to urban air pollution and literature from the ecological domain addressing urban green cover and its potential to abate urban air pollution. This literature is discussed in the light of European geography of air pollution and green cover. Building on these findings, I contribute to the existing literature by extrapolating on a stylized scenario of an increase of urban green infrastructure of 1 m2 per head of EU urban population and obtaining expected value of social benefit resulting from air pollution abatement and carbon sequestration. It is important to note, however, that the resulting numbers reflect only a part of total social benefit of urban green infrastructure, as it brings a whole array of other (co-)benefits such as aesthetics, noise attenuation and water management.

The paper is structured as follows. First, we take stock of the extent and geography of air pollution and green urban cover in the EU (Section 2). Next, we present an umbrella review of studies on the impact of green infrastructure on the urban air quality. The focus lies on the ability to reduce air pollutant levels of different vegetation forms in different urban morphologies (Section 3). We follow with a review of studies concerning the social externality costs of air pollutants (Section 4). In Section 5, we take a stylized case of uniform increase in vegetation by 1 m2 per urban inhabitant in order to estimate the benefits resulting from the avoided costs of air pollution and carbon sequestration. We finalise with discussion, limitations and conclusions in Section 6.

2. EU Air Quality and Green Coverage

For the overview of the air quality and green coverage in the EU we have used the data from European Environment Agency (EEA)[13].

2.1. EU air quality

In this section, data from EEA regarding specific levels of various air pollutants in different European countries will be reviewed. It is important to point out that countries differ in the number of reporting stations, which calls for a caution in interpretation of results. Air pollution affects everyone; however, certain regions are more susceptible to its effects. For instance, in southern and central eastern Europe, energy poverty is the reason for combustion of low-quality solid fuels,

[13] EEA 2019, „Air Quality in Europe-2019 Report“, *European Environment Agency (EEA),* doi:10.2800/822355.

such as coal and wood, in low efficiency ovens for domestic heating[14]. This results in high exposure of the low-income population to PM, both indoors and outdoors.

Data on the percentage of urban population exposed to concentrations above EU standards for selected air pollutants and countries (Table 1, respective air pollutant EEA norms are provided in Table 2) generally corresponds to the data on particulate matter (PM), ground ozone (O3) and nitrogen dioxide (NO2) levels (see Figure 1), which contribute to poor air quality in many European areas, despite many achieved reductions in emissions (EEA, 2019), in particular:

1. Exposure to levels of NO2 above the EU reference values is the highest in countries such as Belgium, Germany, Italy, and United Kingdom;
2. Ozone concentrations pose the biggest problem for populations in Mediterranean basin (Croatia, France, Greece and Spain), and Austria
3. Exposure of urban population to particulate matter is the highest in Central and Eastern European countries, such as Czech Republic, Hungary, Latvia, Romania and Slovakia

Based on these data, we observe that regions within the EU that witness the highest levels of air pollution are the countries around the Mediterranean Sea basin and the Central European countries.

2.2. EU green coverage

This section focuses on studies addressing the green coverage in European countries and in a selection of cities. Reported results vary substantially in terms of units and indicators used across the various studies. The Dutch "Green City Guidelines" project suggests that every resident household should be within 500-m from some type of green network[15]. Comparatively, Berlin, Germany aims to provide at least 6 m2 of urban green space per person[16]. Finally, European Environment Agency suggests that people should be able to have access to green space within a 15-minute walking distance (approximately 900-1000 m)[17].

The majority of the population living in Scandinavia or in Western European countries has access to green space within 500-m distance[18]. Some cities in

[14] Ibid.

[15] ROO, M.D., KUYPERS, V., LENZHOLZER, S. *The green city guidelines: techniques for a healthy liveable city.* The Green City, 2011.

[16] KABISCH, N., STROHBACH, M., HAASE, D., KRONENBERG, J. Urban green space availability in European cities. *Ecological Indicators,* 2016, vol. 70, pp. 586–596.

[17] STANNERS, D. and BOURDEAU, P. *Europe's environment: the Dobris assessment.* European Environment Agency Copenhagen, 1995.

[18] KABISCH, N., STROHBACH, M., HAASE, D., KRONENBERG, J. Urban green space availability in European cities. *Ecological Indicators,* 2016, vol. 70, pp. 586–596.

Eastern European countries show high values as well. On the other hand, cities in Southern European countries exhibit relatively low values of green accessibility. Besides, there is a spatial heterogeneity in the distribution of green space in EU countries, with lowest provision of per capita green space in the South and East of Europe, increasing to the North and West[19]. This is presented in Figure 2.

Figure 3 shows the percentage of urban green coverage as a percentage of total urban area, with most of the cities possessing 30% or less of green coverage. Combined with Figure 5, these data reveal that Southern European countries suffer from a lack of urban green space, especially in Bulgaria, Greece, Italy and Spain. Northern and Western European countries are doing significantly better, although the EU most densely populated Netherlands and Belgium seem to be struggling as well, with both countries reporting a cluster of relatively low percentage of urban green space.

Based on the studies reviewed in this section, we observe that regions within the EU that witness the highest levels of air pollution are also the regions which are relatively poor in urban green coverage and the availability of green infrastructure to urban residents. In particular, these are the countries around the Mediterranean Sea basin and the Central European countries. We can thus identify these regions and their urban areas as the ones which would benefit most from improved urban green infrastructure to improve air quality performance in Europe.

3. Review of Studies on the Impact of Green Infrastructure on Urban Air Pollution

In order to establish whether and how green coverage contributes to the improvement of urban air quality we have conducted an umbrella review[20] of studies that summarised existing primary studies on the impact of green infrastructure on urban air pollution. For the search process, we used databases such as Google Scholar and ScienceDirect. The following search terms were used: *"green infrastructure", "absorption level", "street canyons", "local pollution", "background pollution", "green walls"* and *"green roofs"*. We focused on most

[19] FULLER, R.A., GASTON, K.J. The scaling of green space coverage in European cities. *Biology letters,* 2009, vol. 5(3), pp. 352–355.

[20] AROMATARIS, E., FERNANDEZ, R., GODFREY, C.M., HOLLY, C., KHALIL, H., TUNGPUNKOM, P. Summarizing systematic reviews: methodological development, conduct and reporting of an umbrella review approach. *International journal of evidence-based healthcare,* 2015, vol. 13(3), pp. 132–140.

recent review papers, mainly papers published in the last 5 years. The selected publications complied with the following criteria:

1. Papers written in English
2. Peer-reviewed articles, i.e. articles published in academic journals
3. Official reports of established national and international institutions

There are two sources of pollutants in urban areas, namely local pollution and background pollution. Whereas background pollution is the one transported from other areas of origin where pollutants may travel even over long distances, local emissions are the ones that originate in cities themselves[21]. In recent years, intensive research has been done to understand the effects of green infrastructure abating air pollution. These studies have a wide scope. One of the directions within this string of literature is the study on air pollution abatement performance of different kinds of green infrastructure. For instance, Nowak et al. (2006)[22] reports median value for air pollutant absorption by urban trees and shrubs of 10,8g/m2/year. Yang et al. (2008)[23] provides a similar number equivalent of 8,5g/m2/year for urban green roofs based on the dry deposition model. Shfique et al. (2020)[24] report values for carbon sequestration by various types of green roof vegetation, ranging between 0,33 and 1,89 kg/m2/year, with 4 out of 7 values above 1,70 kg/m2/year. Another important finding made in this string of literature is the role of green infrastructure in relation to city morphology, and in particular the distinction between street canyons and open roads. Street canyons are a very common urban feature and usually consist of buildings along both sides of the road[25]. The typical green infrastructure in these street canyons can be classified as trees and hedges[26]. Open roads, on the other hand, can be described as an urban built environment

[21] KUMAR, P., DRUCKMAN, A., GALLAGHER, J., GATERSLEBEN, B., ALLISON, S., EISENMAN, T. S., HOANG, U., HAMA, S., TIWARI, A., SHARMA, A. The nexus between air pollution, green infrastructure and human health. Environment international, 2019, vol. 133, pp. 105181.

[22] NOWAK, D.J., CRANE, D.E., STEVENS, J.C. Air pollution removal by urban trees and shrubs in the United States. *Urban forestry & urban greening,* 2006, vol. 4(3-4), pp. 115–123.

[23] YANG, J., YU, Q., GONG, P. Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment,* 2008, vol. 42(31), pp. 7266–7273.

[24] SHAFIQUE, M., AZAM, A., RAFIQ, M., ATEEQ, M., LUO, X. An overview of life cycle assessment of green roofs. *Journal of Cleaner Production,* 2020, vol. 250, pp. 119471.

[25] KUMAR, P., KETZEL, M., VARDOULAKIS, S., PIRJOLA, L., BRITTER, R. Dynamics and dispersion modelling of nanoparticles from road traffic in the urban atmospheric environment – a review. *Journal of Aerosol Science,* 2011, vol. 42(9), pp. 580–603.
VARDOULAKIS, S., FISHER, B.E., PERICLEOUS, K., GONZALEZ-FLESCA, N. Modelling air quality in street canyons: a review. *Atmospheric Environment,* 2003, vol. 37(2), pp. 155–182.

[26] ABHIJITH, K., KUMAR, P., GALLAGHER, J., MCNABOLA, A., BALDAUF, R., PILLA, F., BRODERICK, B., DI SABATINO, S., PULVIRENTI, B. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review. *Atmospheric Environment,* 2017, vol. 162, pp. 71–86.

feature, in which both sides of the traffic corridor are open with detached or single buildings[27]. In these conditions, trees as well as hedges, shrubs and bushes occur along the sides of the corridors and can be referred to as vegetation barriers or green belts[28]. With detailed quantification of local scale aerodynamic effects and reduction potentials of various types of urban vegetation in street canyons as well as open-road configurations, research found that in a street canyon, trees as a form of high-level green infrastructure have, in general, a negative impact on air quality [29], whereas hedges as a form of low-level dense vegetation, show a positive impact. These findings therefore confirm that changes in air quality in a street canyon depend on a combination of various factors, such as aspect ratio (i.e. 'canyon' depth), wind direction and vegetation density.

The literature concerning the effect of trees and bushes on air quality in open roads are mixed[30] with both positive and negative effects reported. Many studies reported reductions in concentrations between 15% and 60% for various pollutants with vegetation barriers along open roads[31]. Similarly, they show that vegetation barriers that are thick, dense and tall have a positive impact on air quality in open road conditions. In particular, vegetation not prone to seasonal effects (such as some evergreen species) are most suitable vegetation barriers in these open road environments. On top of that, vegetation barriers that are closer to the pollutant source result in a considerable pollutant removal. Similar to findings on street canyon studies, climate and regional conditions, as well as differences between cooler and warmer climatic regions play a role in the impact of vegetation on air quality and need further[32].

One of the substantial benefits, beyond air quality regulation, that green infrastructure brings to urban inhabitants is its local climate regulation and in particular, the local cooling effects. This is an important argument in favour of 'stacking' the benefits of urban green infrastructure for its preservation and expansion. For instance, review studies of Hunter et al. (2014)[33] and Pérez et al.

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[27] Idem.

[28] BRANTLEY, H.L., HAGLER, G.S., DESHMUKH, P.J., BALDAUF, R.W. Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter. *Science of the Total Environment,* 2014, vol. 468, pp. 120–129.

[29] ABHIJITH et al., 2017, with the exception of AMORIM, J., RODRIGUES, V., TAVARES, R., VALENTE, J., BORREGO, C. CFD modelling of the aerodynamic effect of trees on urban air pollution dispersion. *Science of the Total Environment,* 2013, vol. 461, pp. 541–551.

[30] Ibid.

[31] Ibid.

[32] Ibid.

[33] HUNTER, A. M., WILLIAMS, N. S., RAYNER, J. P., AYE, L., HES, D., LIVESLEY, S. J. Quantifying the thermal performance of green façades: A critical review. *Ecological Engineering,* 2014, vol. 63, pp. 102–113.

(2014)[34] report on the ability of vertical greenery to improve thermal comfort and energy savings in buildings. In general, the results of these studies suggest that the application of green walls or facades can lead to a reduction in surface temperatures of building facades between 1° and 15° in warm temperature climates. Other studies consistently report on the positive effect of green roofs on mitigating urban heat island effect[35]. Advantages featuring urban greening through green roofs and facades are the low pressure on often scarce urban space.

Our umbrella review shows that the role of urban vegetation in relation to air purification is a many-faceted issue and does not lend itself to be simplified to a rule of thumb type of heuristics. The amount of air pollutant absorption, as well as overall effect (positive, neutral or even negative) on the ambient pollution level depends on a combination of multiple factors, all of which act simultaneously. These factors are the origin of air pollution (local or background), urban morphology (street canyon vs open street), type and source of air pollution, weather conditions (wind strength and direction, availability of rain), seasonality and climate, type of green nature and green species in the vegetation.

4. Review of Air Pollution Valuation Studies

This part of the paper provides a second umbrella review of studies estimating social externality costs connected to urban air pollution. For the search process, we used the same procedure and criteria as described in section 3. The search terms were now divided into two strings: the first one related to the physical aspect of air quality and *"air pollution", "pollutants", "sulphur dioxide", "nitrogen oxides", "ozone", "air quality",* and the second one related to the monetization aspect and included *"social costs", "welfare loss"* and "*environmental valuation"*. We focused on recent papers, published after 2005.

Economic valuation intends to infer values of non-market goods and services that are comparable to other traded goods and services. However, in order to place an economic value on a non-market good, various components that comprise the total economic value need to be identified[36]. This total economic value of environmental goods comprises the direct and indirect use values, and a non-use value. The valuation approaches are divided into valuation approaches according

34 PERÉZ et al., 2014.

35 ESTRADA, F., BOTZEN, W.W., TOL, R.S. A global economic assessment of city policies to reduce climate change impacts. *Nature Climate Change,* 2017, vol. 7(6), pp. 403–406.

36 ABDULLAH, S., MARKANDYA, A., NUNES, P. Introduction to economic valuation methods. *Research tools in natural resource and environmental economics,* 2011, pp. 143–187.

to market data and non-market methods of stated and revealed preference[37]. However, while based on actual transactions data, a common disadvantage of the revealed preference approach is that available studies such as hedonic pricing account only for the use value of environmental amenities thus neglecting the non-use value, and often provide WTP estimates for a specific group of population such as homeowners.

Another set of literature focuses primarily on the revealed preference valuation methods that cover both use and non-use value of environmental amenities, and are based on the survey data from broader populations with stated willingness to pay for air quality. Our review has shown that the publications using stated preference method vary greatly in a number of factors. Some studies focus on valuation of fatality risk due to air pollution in general, while others concentrate on the monetisation of value for a specific pollutant, such as particulate matter, nitrogen oxides, ozone or sulphur dioxide. For example, studies estimating the value of decreasing a risk of a disease related to air pollution in various locations in China or decreasing the risk of fatality related to air pollution in France[38]. Other studies using such approaches as contingent valuation or choice experiments from the stated preference arsenal elicited the value of NOx in Sweden[39].

In addition to academic publications, established national and international organisations publish reports and studies with relevant outcomes. CE Delft[40] reports on environmental prices for the loss of economic welfare for an additional kilogram of a specific air pollutant. These values are based on the willingness-to-pay estimates of social cost of air pollutants and are recommended for use in social cost-benefit analyses. The central values for a selection of pollutants from this study are found in Table 2.

Table 3 summarises the monetary values from our review for the most frequently studied air pollutants, O3, NOx, SO2, PM10 and PM2,5. This table also provides respective standardised values in constant euros per kg pollutant. We observe that WTP-based estimates of pollutant marginal costs greatly agree across various studies, contexts and methods applied, with the only exception of PM2,5

37 Ibid.

38 HAMMITT, J.K., ZHOU, Y. The economic value of air-pollution-related health risks in China: a contingent valuation study. *Environmental and Resource Economics,* 2006, vol. 33(3), pp. 399–423.
CHANEL, O., LUCHINI, S. Monetary values for air pollution risk of death: a contingent valuation survey, 2008.

39 CARLSSON, F., JOHANSSON-STENMAN, O. Willingness to pay for improved air quality in Sweden. *Applied Economics,* 2000, vol. 32(6), pp. 661–669.

40 DE BRUYN, S., AHDOUR, S., BIJLEVELD, M., DE GRAAFF, L., SCHEP, E., SCHROTEN, A., VERGEER, R. Environmental prices handbook 2017-methods and numbers for valuation of environmental impacts. *Delft: CE Delft*, 2018, pp. 05-2018.

value, which is stands out in the DEFRA guidelines[41]. This provides us with a first evidence of the prevailing level of environmental pricing of air pollutants.

5. Illustration: Estimated Social Benefit from Expanding Green Infrastructure in the EU

On average 40% of the EU cities are covered with green, and there is on average about 18m2 of green urban cover available per urban inhabitant[42]. While an absolute minimum of green cover is set at 9 m2 per person and an estimated ideal amount of green coverage per person is 50 m2[43], EU cities resemble a high heterogeneity in terms of green coverage ranging between just a few m2 per person to a couple of hundreds m2 per person (Figure 5). This means that a substantial number of cities do not manage to provide the suggested minimum level of urban green infrastructure for public use to its inhabitants. In particular, in the cities around the Mediterranean basin of the EU, lack of appropriate green coverage even further aggravates the consequences of poor air quality. Besides, in most cases, urban cores depict a lower degree of green elements, leaving a substantial part of the urban population deprived of public green facilities in their daily lives. We shall start with a stylised application for a uniform EU-wide increase in urban coverage in order to establish an idea about the marginal improvement in EU urban green and its effect on urban air pollution. As a next step, we shall zoom in a selection of EU cities form the Mediterranean and Central Europe areas.

In this section, we choose for a uniform, EU-wide scenario because specific focus on the Mediterranean and Central European countries would require a much more complex exercise with a broad range of indicators necessary to derive feasible location-specific estimates, which is outside the scope of this paper. We shall thus explore a blueprint scenario of 1 m2 increase of urban green space

[41] DE BRUYN, S., AHDOUR, S., BIJLEVELD, M., DE GRAAFF, L., SCHEP, E., SCHROTEN, A. and VERGEER, R. Environmental prices handbook 2017-methods and numbers for valuation of environmental impacts. *Delft: CE Delft,* 2018, pp. 05-2018.
HOLLAND, M., WAGNER, A., DAVIES, T., SPADARO, J., ADAMS, M. *Revealing the costs of air pollution from industrial facilities in Europe,* 2011.
BIRCHBY, D., STEDMAN, J., WHITING, S., VEDRENNE, M. Air Quality damage cost update 2019, DEFRA, UK. 2019.

[42] VANDECASTEELE, I., BARANZELLI, C., SIRAGUSA, A., AURAMBOUT, J., ALBERTI, V., ALONSO RAPOSO, M., ATTARDO, C., AUTERI, D., BARRANCO, R., BATISTA E SILVA, F. The Future of Cities—Opportunities, Challenges and the Way Forward. *Luxembourg: Publications Office,* 2019.

[43] RUSSO, A., CIRELLA, G. T. Modern compact cities: how much greenery do we need? *International journal of environmental research and public health,* 2018, vol. 15(10), pp. 2180.

throughout the EU cities and focus on the air pollution and carbon sequestration benefits. With the total EU population of 445 million, urban EU population makes up 74% and about 330 million people. A uniform increase in urban green space of 1 m2 per urban inhabitant would imply additional 3.300 hectares of urban green space. The implications for the types of such green space are discussed further in this paper. To estimate the amount of avoided pollution we have used the weighted average of air pollutant absorption rates for green cover of 10,8gr per m2 per year and 8,5g/m2/year[44]. Therefore, using the absorption rate of 9,65g/m2/year resulted in a total of 3.177.745kg of avoided air pollutants per year. This overall absorption included various air pollutants, that were assumed to account for various relative weights, such as 52% by O3, 27% by NO2, 14% by PM10 and 7% by SO2[45] and allowed us to calculate the amount of each pollutant absorbed. As a final step, we used the central values of externality costs for air pollutants[46], which provide the complete list of recent estimates of marginal social costs of air pollutants, and are in line with previous estimates as reported above and in Table 3. Overall monetary value of avoided social costs related to air pollution is thus estimated at 28.637.130 euro per year, or about 873 euros per year per hectare of additional urban green space (social benefit values per pollutant at the EU level are also found underneath Table 3). The benefit of carbon sequestration was estimated in a similar way, with vegetation productivity of 1,7kg per m2 per year[47] and 0,06 euros per kg of CO2[48], arriving at the total amount of 33.731.184 euro per year. This is equivalent to 1.024 euros per year per hectare of additional urban green space. Therefore, the overall social benefit of air pollution and carbon absorption is estimated at 62.368.314 euros per year. It is important to note that this is not a one-time benefit, as the green infrastructure continues to absorb air pollutants for many years. Thus, we calculated the present value of the EU-wide benefit for a period of 10 years, using a selection of discount rates. The expected benefit ranges from 590 mln euro with the discount rate of 1%, 545

44 NOWAK, D. J., CRANE, D.E., STEVENS, J. C. Air pollution removal by urban trees and shrubs in the United States. *Urban forestry & urban greening,* 2006, vol. 4(3-4), pp. 115–123. and YANG, J., YU, Q., GONG, P. Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment,* 2008, vol. 42(31), pp. 7266–7273, respectively.

45 Ibid.

46 DE BRUYN, S., AHDOUR, S., BIJLEVELD, M., DE GRAAFF, L., SCHEP, E., SCHROTEN, A., VERGEER, R. Environmental prices handbook 2017-methods and numbers for valuation of environmental impacts. *Delft: CE Delft,* 2018, pp. 05-2018.

47 YANG, J., YU, Q., GONG, P. Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment,* 2008, vol. 42(31), pp. 7266–7273.

48 DE BRUYN, S., AHDOUR, S., BIJLEVELD, M., DE GRAAFF, L., SCHEP, E., SCHROTEN, A., VERGEER, R. Environmental prices handbook 2017-methods and numbers for valuation of environmental impacts. *Delft: CE Delft,* 2018, pp. 05-2018.

mln euro with the discount rate of 2,5%, to 383 mln euro with the discount rate of 10%. Choosing an array of discount rates allows for more realistic scenario, as the choice of an appropriate discount rate is a matter of theoretical and practical choice, and remains a source of discussion among (environmental) economists as well as among practitioners.

We note here that the value of social benefit related to decreased air pollution and carbon abatement are of the same order, and both are comparable to the average total value of urban green space in Europe, ranging between 3.166 euros for an urban forest, 7.308 euro for a small urban green and green connected to grey infrastructure, and 34.979 euro for an urban park, all values per ha per year in 2020 euros[49]. We note that other important benefits of urban green infrastructure reflected in its total economic value, alongside air pollution and carbon sequestration include, but are not limited to, health benefits, cooling effects, reduction in noise pollution, water retention, biodiversity and aesthetics. Thus the total expected benefit of additional 1m2 green cover per inhabitant throughout EU cities could then amount between 104,25 mln euros and 1,15 bn euros per year, and would reflect total social benefit to the EU urban inhabitants.

The estimated benefits as above are based on average values at the EU level. The expected monetary benefits for a particular city may vary, and may depend on the income level and the prevailing pollution level. We have selected a number of cities with low amount of green cover and high air pollution concentrations, to illustrate that. Thus, the benefits for removing PM10 from the air can be expected to be higher e.g. in Milan (Italy), and those from removing NOx and SOx – higher e.g. in Lodz (Poland), see Table 4 with country-specific ranges of social costs for each pollutant. Also, the value of total social benefit may vary per city and type of urban nature chosen, mounting to several orders of magnitude compared to the mean value, as illustrated in previous research[50].

6. Conclusions: results, limitations and policy implications

6.1. Results

In this paper, we aimed at pooling together two strings of literature and show the added value of green infrastructure in European cities regarding improved

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49 BOCKARJOVA, M., BOTZEN, W. J. W., KOETSE, M. J. Economic valuation of green and blue nature in cities: A meta-analysis. *Ecological Economics,* 2020, vol. 169, pp. 106480.

50 Ibid.

outdoor air quality. Taking stock of the air quality in Europe, we found a substantial difference between the broadly defined regions of Southern Europe and Northern Europe. In particular, countries such as Italy, Spain, Greece and Bulgaria are suffering from high levels of O3 and PM, relative to countries in Northern Europe. Additionally, we found that PM concentrations are an issue also in Eastern and Central European countries. While most of the (urban) population in Scandinavian, as well as in Western European countries has a fair share of green urban space, urban areas in Southern European countries exhibit relatively low values for green coverage and green urban space per capita.

The studies concerning the impact of green infrastructure on air pollution revealed multifaceted findings. Most studies agree that trees have a negative impact on air pollutant levels in street canyons, where hedges and green facades show a positive impact and are thus more preferred. In the open road environment, most studies reported reductions in concentrations of air pollutants with vegetation barriers along open roads addressing local and background pollution. Moreover, green roofs and green walls showed to be effective, in particular for addressing background pollution level based on the reviewed studies. In addition, there are multiple other benefits of green infrastructure, such as local cooling effect, building insulation, reduction in noise nuisance, water retention, biodiversity and aesthetics.

Estimated unit values of social costs of air pollution originate from a variety of domains and use a variety of methods, including both stated preference and revealed preference approaches. Values of air pollutants that were found expressed per weight unit (g, kg or t) of pollutant are similar in magnitude and so point at general agreement in these estimates across the methods, countries and contexts.

Our stylised exercise of assessing the value of additional green infrastructure across all EU cities of 1m2 per person provided valuable insights into the obtained values of benefit due to improved air quality and carbon sequestration. Both values are about 1.000 euros per hectare on a yearly basis and signify the importance of air quality costs for socially optimal decision-making. Overall social benefit is estimated at 62,3 mln euros per year for air pollution and carbon absorption. The present value for a period of 10 years of this benefit ranges from 590 mln euro to 383 mln euro, depending on the discount rate. The total social benefit of additional 1m2 of urban green per inhabitant for the EU urban residents – between 104,25 mln euros and 1,15 bn euros per year. These total values would reflect all benefits of urban nature, including, but not limited to mental health benefits, local cooling effects, reduction in noise pollution, water retention, biodiversity, aesthetics and so on. Our findings point at generalised results that can be used by practitioners.

6.2. Limitations

It is important to note the limitations of our study. First, the externality costs of air pollutants should be seen as conservative as estimation methodologies are often not able to perform all-round analyses or capture all values. This implies that estimates of avoided costs of air pollution or social benefits associated with the improved air quality should also be seen as conservative. To reflect on the broader benefits of urban green coverage, we have provided a global estimate of the EU-wide total benefits for our scenario based on the central unit values from a recent meta-analysis[51].

Second, although there is a variety of green solutions that can be used, such as trees, hedges, green roofs and green walls, each with their own individual properties and ability to reduce air pollutant concentrations, in our estimates we do not distinguish the type and configuration of green which was not feasible at the scale of this exercise. Applications that take into account prevailing local conditions will prove to be more relavant to the local context and yield the highest benefit.

Third, the scope of this paper did not allow us to explore a more specific scenario of extending the green urban coverage in a particular region and address region-specific features like prevailing weather and climate conditions, prevailing urban morphology and native green species. As a result, the obtained estimate of benefit due to additional green infrastructure may be plausible at the aggregate, but may fall short of benefits provided by a specific type of green, at a specific location or time of the year.

We stress that resulting estimates of air pollutant removal by green infrastructure presented in this paper may be conservative in size, representing the social costs of air quality and carbon sequestration alone. Total economic benefits of urban green infrastructure are higher[52], though also these estimates provide the lower bound due to methodological and data limitations. As argued[53], often WTP-based estimates fail to reflect the full extent of health benefits of green infrastructure through climate regulation, carbon sequestration, prevention of extreme weather, which in turn leads to underselling the importance of green infrastructure.

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51 BOCKARJOVA, M., BOTZEN, W. J. W., KOETSE, M. J. Economic valuation of green and blue nature in cities: A meta-analysis. *Ecological Economics,* 2020, vol. 169, pp. 106480.

52 ibid

53 COUTTS, C., HAHN, M. Green infrastructure, ecosystem services, and human health. *International journal of environmental research and public health,* 2015, vol. 12(8), pp. 9768–9798.

6.3. Policy implications

Green infrastructure and nature-based solutions offer an excellent response to the numerous challenges posed by the changing climate and a potent solution to realise sustainable and healthy cities[54]. Although many European cities need to increase their per capita green cover, creating additional green spaces may prove highly challenging in many urban settings. Our findings point at diverse possibilities and types of urban green that can be implemented, with low spatial pressures. Such solutions may include green roofs, walls and facades, as well as hedges which can be adapted to local weather and climate conditions in terms of native species choice, but all hold high potential to improve ambient air quality and thus the overall welfare of urban population. These types of urban green are also particularly effective in urban street canyons, where street trees deem to be counter-effective by obstructing street ventilation. In order to combat winter peaks of air pollution, evergreen species should be preferred above other types of vegetation. Further research should focus on specific conditions and opportunities of each country and its cities, urban morphology, changing climate conditions and native vegetation in order to provide tailor-made advice and city-specific estimates of the effects and impacts of urban green on air quality, society and economy.

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APPENDIX: TABLES AND FIGURES

Table 1. Percentage of urban population exposed to selected air pollutants above the EU norm

Country	NO2 *annual mean*	O3 *percentile 93.15*	PM2.5 *annual mean*	PM10 *percentile 90.41*
Austria	2.2	18.8	0.0	2.6
Belgium	3.5	0.0	0.0	0.0
Bulgaria	0.5	0.0	0.0	75.7
Croatia	3.3	99.5	17.7	99.1
Czechia	1.4	0.0	12.5	31.3
France	2.0	6.9	0.0	0.4
Germany	4.5	0.7	0.0	0.1
Greece	2.7	96.8	0.0	26.8
Hungary	2.0	51.8	0.0	58.9
Italy	23.8	62.9	75.0	44.2
Latvia	0.0	0.0	0.0	3.8
Luxembourg	4.6	0.0	0.0	0.0
Netherlands	2.0	0.0	0.0	0.0
Norway	0.3	0.0	0.0	0.0
Portugal	2.0	0.0	0.0	0.9
Romania	1.1	35.2	35.5	21.4
Slovakia	0.0	31.8	17.4	40.2
Spain	11.7	22.2	0.0	2.6
Sweden	0.0	0.0	0.0	0.2
Switzerland	3.0	4.6	0.0	0.0
United Kingdom	6.5	0.0	0.0	0.0

Table 2. EEA and WHO air pollution norms

		Air Quality Directive		WHO guidelines	
Pollutant	Averaging period	Objective and legal nature and concentration	Comments	Concentration	Comments
$PM_{2.5}$	One day			25 µg/m³ (*)	99th percentile (3 days/year)
$PM_{2.5}$	Calendar year	Target value, 25 µg/m³	The target value has become a limit value since 1 January 2015	10 µg/m³	
PM_{10}	One day	Limit value, 50 µg/m³	Not to be exceeded on more than 35 days per year.	50 µg/m³ (*)	99th percentile (3 days/year)
PM_{10}	Calendar year	Limit value, 40 µg/m³ (*)		20 µg/m³	
O_3	Maximum daily 8-hour mean	Target value, 120 µg/m³	Not to be exceeded on more than 25 days per year, averaged over three years	100 µg/m³	
NO_2	One hour	Limit value, 200 µg/m³ (*)	Not to be exceeded more than 18 times a calendar year	200 µg/m³ (*)	
NO_2	Calendar year	Limit value, 40 µg/m³		40 µg/m³	

Source: EU Air Quality Directive (2008/50/EC), WHO, 2006, Air quality guidelines: Global update 2005. [online] https://www.eea.europa.eu/themes/air/air-quality-concentrations/air-quality-standards

Table 3. Values of air pollutants found in primary studies.

Studies	Air pollutant	Value (original units)	Standardised values in 2020 €/kg	Comment
Bayer et al. (2006)	Particulate matter PM10	149 to 189 in 1986 USD		for a 1 µg/m^3 reduction in PM10
Luechinger et al. (2009)	Sulphur dioxide SO_2	\$218 to \$318		for the decrease in 1µg/m^3 concentration in SO2
Hammit and Zhou (2005)		\$3 – \$6 \$4 000 – \$17 000		Willingness to pay to prevent an episode of cold Willingness to pay to prevent a statistical case of chronic bronchitis
Chanel and Luchini (2008)		€2.15mil		Mean Value for Preventing a Statistical Fatality
Carlsson and Johansson-Stenman (2000)		2000 SEK/year		Willingness to pay for a 50% reduction of harmful substances
Murray et al. (1994)	Particulate matter PM10 Nitrogen dioxide NO_2 Sulphur dioxide SO_2 Ozone O_3	6614 \$2007/t 9906 \$2007/t 2425 \$2007/t 9906 \$2007/t	**7.612 €/kg** **11.41 €/kg** **2.78 €/kg** **11.41 €/kg**	Externality value of a specific air pollutant
Holland et al. (2011)	Particulate matter PM10 Nitrogen oxides NO_x Sulphur dioxide SO_2	12 560 €/t 7 241 €/t 8 120 €/t	**12.56 €/kg** **7.241 €/kg** **8.12 €/kg**	European average damage cost to health and environment per tonne of emission from industrial facilities
World Bank (2016)	Particulate matter PM2.5	4.8% of GDP		Welfare loss due to ambient particulate matter
De Bruyn et al. (2018)	CO2 Particulate matter PM10 PM2.5 Nitrogen oxides NOx Sulphur dioxide SO2	0.057 €2015/kg 26.6 €2015/kg 38.7 €2015/kg 14.8 €2015/kg 11.5 €2015/kg	**0,060 €/kg** **28,12 €/kg** **40,91€/kg** **15,65 €/kg** **12,16 €/kg**	Loss of economic welfare due to one additional kilogram of a specific pollutant, social marginal value of preventing emissions (central values).
DEFRA (2019)	Particulate matter PM2.5 Nitrogen oxides NOx Sulphur dioxide SO2	105 836 £/t 6 199 £/t 6 273 £/t	**120.656 €/kg** **7.06 €/kg** **7.15 €/kg**	Average damage cost per tonne of emission

Table 4. Estimated benefits of air pollution due to additional green coverage in selected EU cities and EU overall.

Country	City	Urban population	Current GUS (m2/inh.)*	Additional GUS (ha)	Pollutant**	Unit value of benefit – LB (2020 EUR/kg)	Unit value of benefit – UB (2020 EUR/kg)	Benefit of avoided air pollution – LB (2020 EUR/kg/year)	Benefit of avoided air pollution – UB (2020 EUR/kg/year)
IT	**Milan**	**1,35 mln**	**9-20 m²**	135				98.441	270.514
					NOx	10,55	28,22	37.122	99.271
					SOx	10,46	28,86	9.542	26.314
					PM10	28,39	79,46	51.777	144.929
BG	**Plovdiv**	**669.334**	**9-20 m²**	67				59.149	160.341
					NOx	7,36	19,22	25.896	67.605
					SOx	5,54	15,13	5.051	13.797
					PM10	15,46	43,28	28.202	78.938
ES	**Barcelona**	**5,575 mln**	**< 4.5 m²**	558				47.824	128.769
					NOx	3,21	7,63	11.306	26.831
					SOx	7,04	19,40	6.418	17.687
					PM10	16,50	46,19	30.100	84.251
EL	**Thessaloniki**	**1,105 mln**	**< 4.5 m²**	111				42.673	114.905
					NOx	2,25	5,11	7.902	17.963
					SOx	4,50	12,18	4.103	11.103
					PM10	16,81	47,06	30.667	85.839
PL	**Lodz**	**728.892**	**9-20 m²**	73				85.370	234.946
					NOx	11,91	32,26	41.882	113.489
					SOx	11,25	31,19	10.258	28.443
					PM10	18,22	51,00	33.230	93.014
EU		**329,300 mln**	**18,1 m²**	32.930				28.637.130	
					NOx	15,65		13.423.340	
					SOx	12,16		2.704.151	
					PM10	28,12		12.509.639	

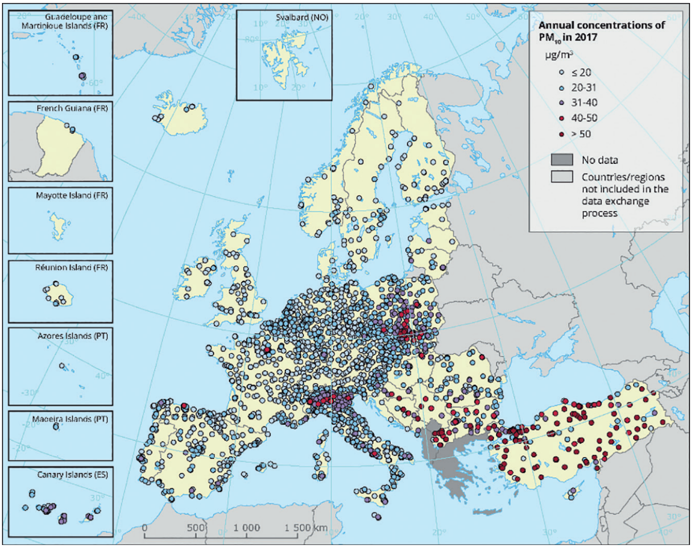
* GUS: green urban space

** Unit value ranges per country are adopted from from EEA (2011); central values for EU-28 are adopted from de Bruyn et al. (2018)

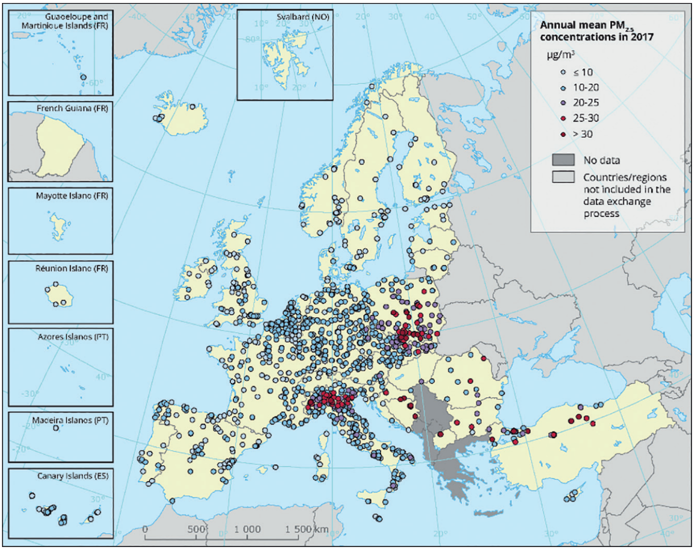
Source: own calculation.

Figure 1. Yearly concentrations of air pollutants in the EU (A – PM10, B – PM2.5, C – O3, D – NO2)

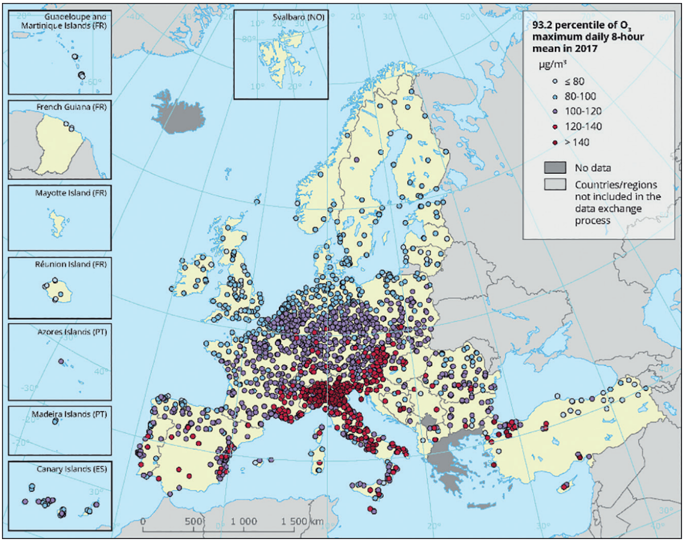
A



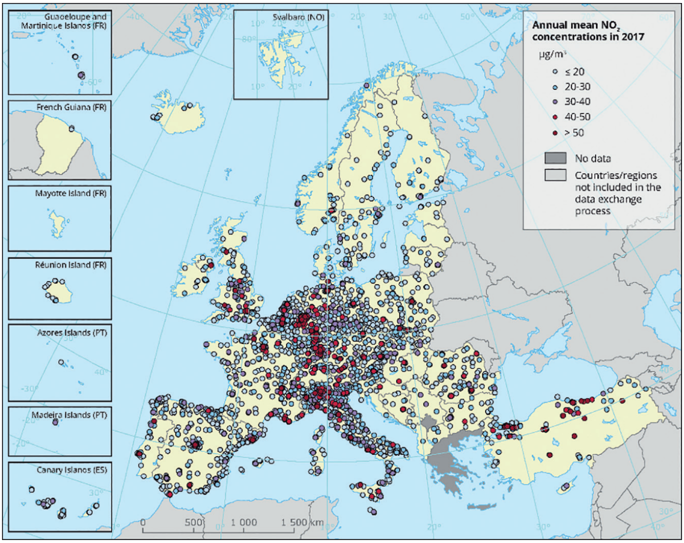
B



C

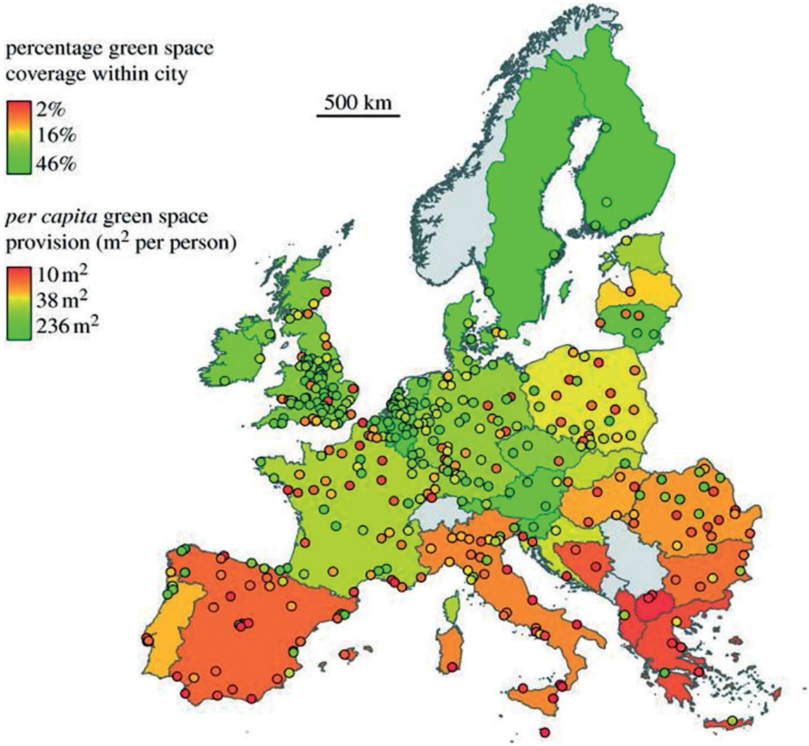


D



Source: Fuller and Gaston (2009)

Figure 2. Green space coverage (country level) and per capita green space (city level)



Source: EEA <https://www.eea.europa.eu/data-and-maps/figures/percentage-of-green-urban-areas-1>

Figure 3. Percentage of green urban cover (city level)