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Review

Role of Vegetation as a Mitigating Factor in the Urban Context

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Abstract: It is known that the urban environment amplifies the effects of climate change, sometimes with disastrous consequences that put people at risk. These aspects can be affected by urban vegetation and planting design but, while there are thousands of papers related to the effects of climate change, a relatively limited number of them are directly aimed at investigating the role of vegetation as a mitigating factor in the urban context. This paper focuses on reviewing the research on the role of urban vegetation in alleviating the adverse conditions of the urban environment in order to provide some practical guidelines to be applied by city planners. Through an analysis of the documents found in Scopus, Web of Science, and Google Scholar using urban vegetation and climate change-related keywords we selected five major issues related to the urban environment: (1) particulate matter, (2) gaseous pollution, (3) noise pollution, (4) water runoff, (5) urban heat island effect. The analysis of existing knowledge reported here indicates that the roles of urban vegetation on the adverse effect of climate change could not be simply deemed positive or negative, because the role of urban green is also strongly linked to the structure, composition, and distribution of vegetation, as well as to the criteria used for management. Therefore, it could help to better understand the roles of urban green as a complex system and provide the foundation for future studies.

Keywords: urban green; urban forest; urban pollution; urban heat island; noise mitigation; city resilience

1. Introduction

Rapid global urbanization, along with extreme weather-related events are exacerbating the impact of environmental threats such as floods, tropical cyclones, and heat waves often associated with dry periods [1,2]. Due to the physical density and population of cities, such threats often result in human and financial losses, pushing cities around the world to learn about the best governance and planning strategies to address issues of equity, livability, and sustainability [3].

In the modern world, urban green is considered and realized as an authentic public service, such as aqueducts, schools, sewers, roads, etc., essential for the life of people, for both their mental and physical well-being [4]. For instance, urban vegetation provides many ecosystem services, which are defined as "benefits people receive from an ecosystem" [5,6]. For example, trees in urban areas can moderate temperatures by providing shade and cooling air by transpiration, thus helping reduce the risk of heat-related illnesses for city dwellers [7,8]. Moreover, trees act as sinks of CO_2 from the atmosphere, by the photosynthetic process and by building up their biomass.

In addition to direct carbon assimilation and storage, the net saves in carbon emissions that can be indirectly achieved by urban planting can be up to 18 kg CO_2/year per tree. This benefit corresponds to that provided by three to five forest trees of similar size and health, as indicated by research carried out in Los Angeles comparing urban vs. forest trees, which suggested that urban trees play a major role in sequestering CO_2 and thereby delaying global warming [9,10]. Similarly, vegetation barriers and green roofs can attenuate noise, provide windbreaks to protect buildings and intercept and filter stormwater runoff [11].

For these reasons, and for their decisive function against air pollution [12], green areas are crucial for promoting human well-being, but also represent a central element to mitigate climate change.

As a consequence, urban planning actions are increasingly addressing not only economic and environmental priorities, but also public health objectives. Therefore, cities are adopting agendas increasingly focused on the relationship among urban territory, natural resources, and human health. In this paper the role of vegetation as a mitigating factor in the urban context is examined in order to provide some practical guidelines to be applied by city planners. In particular, this paper focuses on major issues which threaten human well-being in cities worldwide in the Anthropocene, namely solid, gaseous and noise pollution, water runoff, and the urban heat island effect, to summarize the mitigation potential of vegetation against such stresses.

2. Methodology

The methodology used for this review work is described by Pullin and Stewart [13]. After setting the review question ("what is the role of urban vegetation in mitigating climate change?), a literature analysis was conducted within the scientific databases Scopus, Web of Science, and Google Scholar by using two main categories of relevant keywords ("urban vegetation keywords" and "climate-change keywords") searched in combination using the AND operator:

- "urban vegetation keywords": "urban vegetation"; "urban trees"; "urban forest"; "urban green areas";
- "climate-change keywords": "climate change"; "resilience"; "particulate matter"; "gaseous pollution"; "VOC"; "nitrogen oxides"; "ozone"; "urban heat island"; "noise pollution", "water runoff".

For an article captured by our search to be relevant for the review it was required to meet the following inclusion criteria:

- To be a full text paper (including original research and reviews), peer-reviewed, available in English.
- To include a relevant subject: anyone reporting how urban vegetation can mitigate the effects of human exposures to: (1) particulate matter, (2) gaseous pollution, (3) noise pollution, (4) water runoff, and (5) urban heat island.
- In addition, we selected papers mainly published between 1990 and 2020 from any geographic location.

Additional milestone articles (n = 7) published before 1990 were added to the literature search.

The initial search, after removing duplicates, returned a total of 16,090 results. Then, papers that did not satisfy the inclusion criteria (i.e., those that were not available in full text, in English language, and that did not specifically report on the five aspects listed above) were excluded. In the first instance, the inclusion criteria were applied to title only in order to efficiently remove clearly irrelevant citations.

Articles remaining (n = 1703) were further filtered by viewing abstracts and then full text, to reach the final list of relevant articles. These articles were checked for their methodological and statistical rigor (e.g., number of replicates, duration of the experiment, observational study with appropriate controls, etc.) which affect the reliability of the data and generality of the study findings.

The remaining 199 relevant articles (+1 cited in the methodology section) formed the basis of this review, with 13 papers addressing general topics about ecosystem benefits of urban green infrastructures in mitigating climate change, 77 papers addressing the topic "particulate matter", 19 "gaseous pollution", 17 "noise pollution", 18 "water runoff", and 55 the "urban heat island" effect.

3. Particulate Matter

Air pollution has reached worrying levels, especially in certain urban areas of the planet where it produces what is commonly called "background contamination" [14]. Among the pollutants, particulate matters (PM_x) are considered to have a major health impact, as their effects on the human body differ for different size classes, introducing an extra complication compared with gaseous pollutants [15].

Although scientific evidence does not provide any threshold under which exposure to PM_x would not cause harmful effects [16], a number of studies have shown that increased mortality is associated with short- and long-term exposure to PM, both in developed and developing countries (see review in [17,18]). For instance, it was estimated that in 2015 approximately 4 million premature deaths were caused by fine particulates and this value could reach an estimated amount of 6.6 million by 2050 [18–21].

Epidemiologic studies have reported statistical associations between day-to-day changes in health outcomes, such as daily mortality, and day-to-day variations of indicators of daily ambient particulate matter (PM) concentrations, most frequently total suspended particulate (TSP) matter or PM_{10} [22].

Particulate matter, produced mainly by vehicles, industrial plants, power plants, and heating systems, is formed by solid particles and liquid substances classified according to different diameters in PM_{10}, $PM_{2.5}$, PM_1, and $PM_{0.1}$ (diameter <10 µm, <5 µm, <1 µm, and <0.1 µm, respectively) [23].

Street-level concentrations of particulate matter exceed public health standards in many cities, and currently, over 85% of the urban European Union (EU) population are exposed to PM levels higher than the values indicated in the 2005 air quality guidelines issued by the World Health Organization (WHO) [24], although the highest concentrations are measured in China, India, and in all of Southeast Asia. For example, in January 2013 the concentration of $PM_{2.5}$ in Beijing exceeded the value of around 700 $\mu g/m^3$ (a value 15–17 times higher than the current limit in Europe) and a study provided evidence that $PM_{2.5}$ pollution increased the risk of respiratory emergency room visits in urban areas of the Chinese capital [25].

In recent years, fine particulate air pollution has become an increasingly serious problem for human health as shown by several studies that evidenced how exposure to $PM_{2.5}$ increases the risk for hospital admission for cardiovascular and respiratory diseases [26–28]. More recently the level of PM_x pollution has also been connected to the spread of COVID-19. Conticini et al. [29] showed that the high level of pollution in Northern Italy should be considered an additional co-factor contributing to the extremely high level of lethality recorded in that area, in which about 12% of infected patients die compared to an average of around 6.4% globally.

A large multicenter study published in Lancet [30] showed an association between exposure to atmospheric particulate matter and the incidence of lung cancer, particularly adenocarcinoma, in Europe, which greatly expanded the burden of epidemiological tests. Other significant health effects associated with fine particles with diameters less than 2.5 microns ($PM_{2.5}$) include accelerated atherosclerosis and Alzheimer's disease [31,32].

The regulation of PM pollutants by the US Environmental Protection Agency [33] has led to significant improvements in air quality over the past decade, with reductions in $PM_{2.5}$ from 2000 to 2007 (the average value of $PM_{2.5}$ decreased on average by 11%), associated with a significant decrease in premature deaths in the United States where, according to the data in the literature, the fine particulates alone are responsible for 130,000 deaths per year [34]. However, despite the significant decreases in $PM_{2.5}$ concentrations that have been achieved in recent years [35], there is a need to further improve air quality to reduce health problems.

Pollutant concentrations can be reduced by controlling their emissions as well as increasing dispersion and/or deposition rates [36]. To date, limited attention has been given to this last method for pollution control.

Vegetation performs important ecological functions in cities by removing several classes of pollutants [37]. Some works, aimed at determining what is the entity (quality and quantity) of the particulate accumulated on the leaves, revealed that the effectiveness of urban green against particulate matter can be relevant, because when the particles that flow in a turbulent way hit a leaf, they are guided through the boundary layer to the surface of the leaf, to which they adhere (dry deposition) [38–40]. According to data published in the literature, 1 m^2 of leaf area can absorb between 70 mg and 2.8 g of particulate matter per year [41,42]. Some models developed in the United States within a large-scale project carried out in Chicago showed that 1 ha of trees (with 11% coverage), removed 9.7 kg of pollution in one year (the component on whose action was most relevant was the particulate smaller than 10 µm, about 3.5 kg) [43] and that the removal for the whole city area (around 600 km^2) was 591 tons. The results of Yang et al. [44] showed that trees in central Beijing removed 1241 tons of particulate matter in 2002 (mostly PM_{10}, 772 tons). A work by Nowak et al. [45] linked the removal of $PM_{2.5}$ from trees in 10 US cities with health effects. The total amount of $PM_{2.5}$ removed annually from trees varies from 4.7 tons in Syracuse (NY) to 64.5 tons in Atlanta (GA), with annual values produced by direct and indirect benefits ranging from $1.1 million for Syracuse up to $60.1 million for New York City. Most of these values are given by the effects of reducing human mortality. The reduction in mortality has been estimated at around 1 person/year for different cities, but with a value of 7.6 people/year in New York City. Similar models have also been developed in Europe [39] which demonstrate the effectiveness of trees as "scavengers" of particulate matter with respect to other types of vegetation and other surfaces. Mc Donald et al. [39] showed that a theoretical increase in tree cover, up to a maximum of 54%, would reduce PM_x concentration by 26% in the West Midlands area in the United Kingdom, by removing 200 t of particulate matter per year. Similarly, in Glasgow, an increase in tree cover from 3.6% to 8% would reduce the concentration by 2%.

PM settles on any type of surface at rates that vary depending on the particle diameter, nature of the surface, wind speed, the frequency and intensity of precipitation, and the concentration of the pollutant itself [46,47]. It is known that the leaves of trees, especially those with certain characteristics, can act as a "sink" for suspended particulate, or can capture the polluting particles that are deposited on the leaf surface [48]. In general, the deposition rates on vegetation are much higher than those on metallic and built surfaces [46]. The most important mechanisms by which particles settle on leaf area are sedimentation under gravity, Brownian diffusion, interception, inertial impaction, and turbulent impaction [49]. PM_x, then, will follow two alternative paths: in some cases they will be absorbed by the leaf stomata and will enter, in various ways, into the tree's metabolism; more frequently, they will accumulate on the leaf surface until they are taken to the ground by precipitations or resuspended by the wind [50]. It should be emphasized that absorption is, however, much lower than accumulation and mainly concerns the smaller particles.

Several studies explored the characteristics which influence the adsorption and accumulation of PM on leaf surfaces and revealed that plant traits which mostly affect them are leaf anatomy and canopy architecture. Some species-specific leaf features such as the presence of trichomes [51–53] and the chemical composition and structure of epicuticular waxes [54] could improve this process of "air filtration".

In general, deciduous trees characterized by leaves with rough surfaces are more effective in capturing PM_x than those with smooth surfaces [38,55]. *Elaeagnus*, for example, with a hairy and waxy leaf surface is more effective than smooth-leaved species such as *Ligustrum* [56,57]. Research carried out in Poland [58] found that trapping efficiency largely differed among four shrub and climber species: *Forsythia* × *intermedia* and *Spiraea japonica* were more effective in capturing fine particles than *Physocarpus opulifolius* and *Hedera helix*. Different results were found considering larger particles as well; *Hedera helix* more efficiently trapped large fractions of PM than *Forsythia x intermedia*.

Adhesiveness or stickiness of the leaf further increases retention efficiency [59]. Tree species such as lime (*Tilia platyphyllos*) and birch (*Betula pendula*) often have a layer of sticky honeydew, due to the presence of aphids, which undoubtedly increases adhesiveness to the polluting particles [59,60].

Other species, such as *Acer campestre*, directly secrete honeydew providing the same effect [60]. The needles or needle-like leaves of conifers, which produce a layer of epicuticular wax (i.e., the organic component of the cuticle that covers the external surface of plant tissues), are often more effective in accumulating PM_x than broadleaf [50,61], especially in winter when pollution concentrations are the highest and broadleaf tree species are mostly leafless [62]. On the other hand, most of these plants maintain needles for several years, so the possibility of recycling the PM_x accumulated every year on the needles is lower compared to the deciduous trees. Therefore, evergreen conifers may not be as effective as deciduous species, despite their high efficiency in PM_x scavenging [38,58]. In addition, conifers are not recommended for use in heavily polluted areas because they are susceptible to pollutant-induced injuries [62].

Other determining factors affecting the deposition process are canopy architecture and leaf area density. The architecture of the canopy triggers the formation of swirls and air currents, which are formed when a laminar flow is interrupted by non-aerodynamic, rough or hairy surfaces, and are highly correlated to PM deposition efficiency on tree leaves [63,64]. A high degree of canopy complexity increases the likelihood that micro-turbulences will be created, and in this sense, young plants, or species having compound leaves (such as *Aesculus* and *Fraxinus*), show better performances [38,59].

Deposition increases with leaf area density until a threshold, then decreases for excessively dense canopies, because within a very dense canopy turbulences are suppressed, and deposition may be reduced [65]. Jin et al. [66] developed the particulate matter attenuation coefficient (PMAC) and pointed out that the density of the canopy, the leaf area index (LAI), and the rate of change in wind speed were the most significant predictive factors on the PMAC. Further analysis showed that, in order to balance both environmental and landscape benefits of tree-lined roads, the optimal range of canopy density and LAI were 50%–60% and 1.5–2.0, respectively. Therefore, very dense and evergreen species may not be as effective as expected or, sometimes, even increase the concentration of pollutants [66].

Most adsorbed particles captured by trees can subsequently be removed from the canopies by the wind and/or washed by rain and deposited onto the ground, where the organic components of the PM_x are decomposed while the inorganic components are accumulated in the soil and in the soil solution [45,58]. Therefore, although PM deposition on plant surfaces corresponds to particle removal from the air, thus reducing pollutant concentration, it must also be noted that a part of the trapped PM may be resuspended by wind into the air. Although resuspended particles can be directly inhaled by humans and cause health hazards, a limited body of literature has explored how resuspension occurs in different species and urban micro-climates [67,68]. On the other hand, washoff is the process whereby PM is transferred from plants to the soil during precipitation events [69]. Compared with studies on the accumulation of PM by plants, studies on resuspension and washoff are still scarce, especially those investigating different species and how leaf traits affect these processes [70–72].

According to this, for an accurate estimation of the contribution of vegetation to air quality amelioration, more information is needed on resuspension and washoff of adsorbed PM [70]. Simulated rain experiments and in situ monitoring of the dynamics of PM accumulation on leaves may be useful to obtain such information.

As argued by Janhäll [15], the design and choice of urban green is fundamental when using vegetation to deliver an ecosystem service like the improvement of air quality [1,73–76]. Indeed, several factors, other than plant traits, affect leaf deposition. They include season, concentration of pollutants, wind speed, rainfall, and site geometry that, together, determine the adsorption coefficient (calculated as the percentage of particles actually trapped compared to those that impact the leaf) and the overall effect on air quality [61,77]. Beckett et al. [59], for example, studied this dynamic at four sites in and around London, which differed in terms of vegetation cover, source of pollution, and distance from the pollutant factor. The efficiency in capturing and retaining particles was proved to be, first and foremost, site-specific; then, within the same site, a great variability was found between the species. In a 10 ha park located in Brighton, in the immediate vicinity of a major road, a 21-m-tall English elm (*Ulmus procera*) adsorbed, in a single vegetative season, 1071 g of suspended particulate, corresponding to 475 mg m^{-2} of leaf area. In the same place, a 12-m-tall lime tree absorbed 192 mg m^{-2} of particles, while a plant of very similar characteristics, evaluated in another site (small park of 2 ha in the city), caused a reduction of 488 mg m^{-2} of pollutants.

According to Xing and Brimblecombe [78], we can state that a poor design can degrade air quality in parks with inappropriate plantings and encourage the use of highly polluted zones, while a good design can help eliminate negative health impacts. Therefore, creating new green areas is of paramount importance, and research on air quality in parks needs better links to planning and design [78]. In open spaces, several studies have suggested that roadside vegetation barriers may provide a cost-effective strategy to mitigate near-road air pollution [79–82]. To be effective, the vegetation barriers must be dense enough to offer a large deposition surface but, at the same time, sufficiently porous to allow penetration, instead of deflection of the air flow over the barrier [83].

Fewer, and sometimes contrasting, studies have described the impact of vegetation on air quality in street canyons, a term used to represent streets flanked by buildings on both sides in which pedestrians, cyclists, drivers and, above all, residents, are probably exposed to concentrations of pollutants above the limits established by the WHO and whose characteristics can strongly influence air quality [84]. Research by Pugh et al. [36] showed that dense tree vegetation can increase PM concentrations by up to 60% in street canyons because reduced air turbulence in the busy road canyons results in hindered dispersion [85]. Indeed, plants may represent an obstacle to air flow which can reduce air exchange compared with non-vegetated areas [46]. In contrast, Jeanjean et al. [86] showed that trees have a positive impact on air quality on a local and regional scale thanks to the increase in turbulence and reduction in pollutant concentration of around 7% at pedestrian height. In urban canyons, shrub vegetation near the source of pollutants is highly recommended to improve the air quality, increasing the deposition without hindering the air exchange [83,87].

Therefore, vegetation height and density should be carefully selected based on site-specific micro-climatic conditions to positively impact air quality. In this regard the role of shrubs should not be underestimated [57]. The possibility of being planted at the roadside edge (contrary to what happens for trees) and higher plant density, can guarantee a greater reduction of the concentration of pollutants and, therefore, of their diffusion in nearby areas [87,88]. In this regard, the evergreen species, especially those typical of the Mediterranean habitat, have shown good results in research conducted in Italy [56] and other countries [89,90]. Thus, the choice of species and the design of the plant site could have a great influence on the performance of filtering PM pollutants by urban vegetation [91].

4. Gaseous Pollutants

The gaseous air pollutants of primary concern in urban settings are classified as primary pollutants (emitted directly into the air from anthropogenic activities, such as sulfur oxides (SO_x), especially sulfur dioxide (SO_2), nitrogen oxides (NO_x), and carbon monoxide (CO)) and secondary pollutants that are reaction products of primary pollutants (such as ozone, H_2SO_4, and peroxyacyl nitrates (PAN)). In particular, ozone, a key component of smog, is formed in the lower troposphere, through a series of photochemical reactions, whose main reactants are NO_x and various volatile organic compounds (VOCs) [75,92–94].

Nitrogen oxides, sulfur oxides, and carbon monoxide are produced by the combustion of hydrocarbons [90,95]. They are, on the one hand, directly dangerous for human health and, on the other hand, they can contribute to climate change. Among gaseous pollutants, the evaporative emissions, as well as the exhaust gas emissions during the first minutes of car engine operation (mainly NO_x), are among the most harmful for the local microclimate. For example, NO_2 is 40 times more effective than CO_2 in trapping long-wave radiation reflected from the Earth's surface [96].

Plants remove gaseous pollutants mainly by stomatal absorption [90]. Stomatal uptake depends on both photosynthetic activity and turgor pressure (that vary according to the environmental conditions) as well as on the water-use physiological strategy of the plant. For instance, anisohydric species, which are able to keep their stomata open over extended periods, are more efficient at gaseous pollution uptake than isohydric species, which close their stomata early in response to decreasing water availability. Thus, the selection of anisohydric species such as *Populus* or deciduous oaks—in contrast to isohydric ones such as *Pinus* or *Platanus*—increases stomatal uptake of gaseous pollutants [97].

The uptake through stomata is high as long as the respective compounds are quickly removed from the intercellular spaces [42]. For example, O_3 and NO_2 are almost immediately metabolized, which means that the uptake increases with increasing outside concentrations as long as photosynthesis and membrane permeability are not damaged by the pollutant inflow. Therefore, leaf defense mechanisms can also be considered as species-specific traits affecting gaseous pollution removal. In the case of O_3 and nitrogen oxides (NO_x), for example, the primary mechanism is the detoxification potential of the apoplast, while for SO_2, the transport resistances inside cells and the ability to neutralize changes in pH are crucial [97].

Regarding hydrocarbons, it must be emphasized that 16% of hydrocarbon emissions come from evaporation that occurs during daytime heating from the fuel delivery systems of parked vehicles [98]. By lowering air temperature through shading, urban vegetation reduces the release of anthropogenic VOCs from car engines and solvents and coating materials commonly used in urban environments [99,100]. In particular, the shade of trees can reduce air temperature up to 5–7 °C on hot summer days and this has significant effects on the quantity of volatile hydrocarbons emitted by parked cars [98,99]. Nevertheless, it must be considered that some plant species emit biogenic volatile organic compounds (BVOCs). The emission of BVOCs by plants has been the subject of numerous research projects that have ascertained their function as important chemical messengers produced by plants that give them greater advantages for the reproduction of the individual and survival of the ecosystem [100–102]. Volatile compounds emitted by plants can act as deterrents and repellents to many pests, but they can be attractive to other insects, including pollinators or predators of phytophagous insects [103]. However, due to their chemical nature of unsaturated hydrocarbons, BVOCs interact very rapidly in the presence of light with the constituents of the atmosphere such as ozone (O_3), hydroxyl radicals (OH^-) and, in urban areas, with anthropogenic compounds such as NO_x [104]. The products of the terpene oxidation reaction with O_3, OH, and NO_x include secondary aerosols, PM, and organic acids that can increase acid deposition and air pollution [105]. Therefore, the negative impacts upon air quality associated with BVOC emissions may counteract or even outweigh the gaseous pollution abatement.

In order to minimize these disadvantages, careful species selection is crucial [106]. Primary sources of BVOCs include numerous genera of common urban trees, such as *Populus*, *Salix* and *Platanus* (for isoprene) and *Quercus*, *Malus* and *Pinus* (for monoterpenes) [107,108]. In addition, beyond the genus, BVOC emissions can differ among species. In this context, Donovan et al. [109] developed a sort of quality score that ranks urban trees according to their potential for gaseous pollutant removal versus BVOC emission. Those which scored highest (i.e., most beneficial) among the species investigated were: *Acer campestre*, *Acer platanoides*, *Alnus glutinosa*, *Betula pendula*, *Chamaecyparis lawsoniana*, *Crataegus monogyna*, *Larix decidua*, *Prunus laurocerasus*, and *Pinus nigra* [109]. Nevertheless, the classification of a plant species as beneficial according to its BVOC emission is highly problematic, due to both intraspecific variation as well as the different atmospheric reactivity of BVOCs under different environmental conditions [110].

Advanced air chemistry models that integrate both environmental and physiological plant aspects will be useful in describing BVOC-NO_x-O_3 relationships at different spatial scales and this knowledge can guide city planners and landscape architects in choosing the appropriate vegetation for certain urban sites, particularly in the so-called more polluted "hotspots".

5. Noise Pollution

Living in a quiet area has a positive impact on health [111]. Numerous studies have compared the quality of life for people who live in quiet or noisy areas and discovered that those who live in particularly quiet places, such as in rural areas or within large green areas, have a better quality of life [112]. Together with the above-mentioned advantages, urban vegetation can abate the noise of various human activities by making a certain contribution to acoustic health [113,114].

The sound wave, which is constituted by movement of the air, disperses its energy when it is forced to move along a complex path, degrading itself due to friction in the form of heat. This "obstacle course" can be made up of the channels of the pores of the soil, the leaves, the branches of the vegetation as well as the porosity, holes, and cavities of the artificial barriers [115]. The shape, size, and distribution of obstacles therefore influence the amount of damped energy produced at different frequencies [116,117].

Research carried out in China showed that green building elements can absorb up to 50% of the incident sound energy [118]. Specifically, in the case of plant barriers and green roofs, this attenuation is linked to various factors such as specific composition, morphology, structural parameters, disposition, and possible phytosanitary problems [119].

The distance from the road margin within which the noise reduction by an acoustic, vegetated, and non-acoustic barrier is realized is very variable; however, it is generally recognized that for distances greater than 100–150 m the reduction of noise due to distance makes the use of barriers useless. Therefore, they perform an action in a purely local context [120]. The noise attenuation can be up to 10–12 dB for bands with depths greater than 100 m depending on the species used, the structural characteristics of the barrier, and the distance from the detection [120].

It is important to remember the different behavior of the barrier depending on the frequency of the noise emitted. It has been shown that the range of vegetation efficacy oscillates from 0.5 kHz up to 2 kHz with a recovery of efficacy at high frequencies (from 5 kHz to 8 kHz); this is at the expense of the sensitivity of the human ear whose peak sensitivity is between 2 and 5 kHz. To this, we must add that the noises originating from vehicular traffic have frequencies above all between 0.25 and 2 kHz, a frequency range not completely covered by the protective action of vegetation [121].

Vegetation is not generally a good barrier to noise propagation except for plants with very high thickness [122,123]. To get the same noise reduction that can be obtained using a standard 1.5-m-tall noise barrier, vegetation thickness should be at least 15 m and planting distance should be 1–3 m [124]. The effects of tree stem, tree canopy, and ground covering shrubs on noise attenuation are additive; pluri-stratified vegetation belts are more effective than those made by a single layer of vegetation. Shrub layers with height either lower than 0.5 m or higher than 2 m are recommended for noise abatement [124]. Rectangular planting schemes, if properly planned, are preferred to square or triangle layouts. Properly planned rectangular designs have lower planting distance parallel to the traffic source than perpendicular to it [124].

The vegetation belt should be planted near the source of noise because the rate of attenuation decreases as the distance from the source increases [125]. Finally, because the effect of attenuation produced on low frequency sounds by vegetation is irrelevant [116], adding the action of soil to that of vegetation can result in higher noise abatement compared to vegetation alone [126]. Thus, some types of green areas such as embankments should be extensively integrated along roads to mitigate noise pollution, particularly in those sites where lack of space does not allow the planting of thick vegetation belts.

In addition to the direct effects of plants on noise, it has recently been reported that restorative properties of vegetation, the natural sounds produced by urban green areas, and their capacity to visually hide the source of noise can mitigate the negative effects of noise perception, with an impact on human well-being similar to a 10 dB reduction in noise intensity [127].

6. Water Runoff

Urbanization has consumed land for decades, not only through direct residential and industrial building activities, but also through the extension of the transportation network, such as new railways, new roads, extension of existing roads, and all related infrastructure. Soil sealing and the consequent impermeabilization have direct negative effects on the fundamental gas exchanges between soil and atmosphere and indirectly on the fertility of the soil itself [128,129]; despite tree vitality it may not be directly constrained [130]. Added to this, soil sealing can aggravate the urban heat island effect (Section 7) and further increase the temperatures of cities.

Directly linked to the high level of impermeabilized soil is the problem of regulating water extremes, which has unfortunately become more and more frequent in recent years. Soil covering with impermeable materials reduces or impedes the infiltration of inflows in the ground, increasing the surface runoff which can determine direct and indirect damages. The result, evident in the last few years, is the drastic increase of floods events (especially the so-called "flash floods" [131]) in different parts of the world [132].

The increase of vegetative cover is an effective way to reduce the percentage of impermeable soil. Thanks to the presence of trees and shrubs, but also lawn areas, there is an immediate effect of reducing the impact effect of rainwater through direct interception that delays the outflow [133]. Subsequently, it can be removed by surface lamination and subsequent percolation through draining ducts or slowly absorbing into the soil. Moreover, the presence of trees and the roots of other plants creates an "underground network" that further improves infiltration. Above the surface, plant foliage and natural mulching also contribute in limiting the negative impact of heavy rainfall, thus reducing the amount of soil lost for erosion, keeping it even more fertile [134]. Urban trees can reduce stormwater runoff by intercepting 15% to 27% of annual rainfall [133]. Rainfall entering the tree crown can be partitioned into three pathways: throughfall, stemflow, and interception [135].

Throughfall accounts for precipitation that passes directly through the canopy and water that drips from leaves and branches. Stemflow is the portion intercepted by the canopy that flows down the stems and branches to the ground. Interception accounts for the portion of rainfall that is intercepted by the crown and never reaches the ground surface, thereby not contributing to surface runoff [133,134]. Rainfall interception varies widely among tree species [136]. For example, Asadian and Weiler [137] investigated throughfall losses by urban coniferous trees in Vancouver. They found that average canopy interception varied among species, ranging from 20.4 to 32.3 mm for *Pseudotsuga menziesii* and *Thuja plicata*, respectively. In addition, Xiao and McPherson [133] studied interception losses of 20 urban trees in the Mediterranean climate of central California. The surface storage capacities varied three-fold among these trees, ranging from 0.59 mm for *Lagerstroemia indica* and 1.81 mm for *Picea pungens*. In general, species with the highest leaf surface storage tend to be those with the lowest leaf hydrophobicity and water droplet retention [138]. Other factors include leaf roughness, geometry, and inclination. In addition, bark morphology and branching architecture influence differences in water storage among species [133]. For example, the bark water storage capacity of *Quercus rubra* was 2.5 times higher than *Betula lenta* [139].

According to Baptista et al. [140,141], accurate quantification of rainfall interception is a complex task because it depends on many factors, including environmental conditions (rainfall intensity, wind speed, etc.). It is consolidated, however, that trees intercept rainfall and store part of the water on leaves and branches, reducing the volume and velocity of water that reaches the soil. Moreover, trees modify the spatial distribution of rainwater under the canopy, though there are important differences among species, and these can be altered by management techniques (i.e., topping trees) or by weather extremes (i.e., drought spells can lead to defoliation thus reducing the potential effect of rainfall interception by trees).

Finally, the effect of vegetated areas on the quality of the water going into the aquifer is important, thanks to the higher capacity of the vegetation to remove pollutants conveyed by stormwater than a soil without vegetation. Processes such as biofiltration, based on the removal of polluting substances and other sedimentation particles from rainwater by plants, and simple filtration can mechanically reduce impurities from the soil (thanks to the action of colloids) [142,143].

The exploitation of these processes is based on the creation of green spaces specially designed to reduce the erosive action of rain and to limit the possibility of the so-called "flash flooding" events, infamous for their widespread damage and even human losses.

Despite lower infiltration rates, soil beneath impermeable pavements have been reported to be moister than bare soil, in the absence of trees [128]. Considering that infiltration is hastened by impermeable pavements, higher moisture in sealed soils can be explained by evaporation also being greatly restricted by impermeable pavements. This results in lower latent heat dissipation and higher sensible heat in sealed than in unsealed soil. Thus, it is not surprising that the lower evaporation from sealed soil results in a substantial soil warming, particularly during summer months, when higher air and soil temperatures trigger evaporation in unpaved soil [128]. Warming of deep soil layers can affect surface energy flux and modulate regional climate variation for decades [144], generating the "sub-surface urban heat island" which has been minimally investigated so far [128].

As reported by Baptista and colleagues [140], the reduction of stormwater runoff due to rainfall interception will become increasingly important. Due to climate change, a higher annual amount of precipitation is expected in fewer events. Intensive rainfall events cause quick runoff response in urban areas which can be regulated and lowered by urban vegetation. For example, a 35% reduction in the impermeable surface due to tree planting reduced runoff in a parking lot by almost 18% [145].

Although urban vegetation has an important role in regulating water runoff in urban areas, there is still little knowledge about the best species to choose, the right methods of planting, planting costs, and, finally, the benefits that can be obtained.

7. Urban Heat Island Effect

Our cities are a mix of concrete and asphalt and this may trigger the so-called "urban heat island" effect [146,147], particularly if non-irrigated urban landscapes replace irrigated agriculture land [148,149]. This phenomenon causes a temperature increase of several degrees (up to 12 °C in extreme cases) [150] compared to the surrounding rural areas (together with an influence also on humidity) [147,151,152].

In general, the urban heat island increases with the size of the urban agglomeration and, according to the Environmental Protection Agency (EPA, 2008) [153], many cities in the United States have air temperatures up to 5–6 °C higher than those of the surrounding non-urbanized environment. Similar values (up to 7.26 °C) were found in a study carried out in Japan comparing different types of parking with the presence or absence of trees [154]. Atmospheric urban heat islands are often weak during the morning and throughout the day and become more pronounced after sunset due to the slow release of heat from urban infrastructures. The timing of this peak, however, depends on the properties of urban and rural surfaces, the season, and prevailing weather conditions [153]. Surface temperatures have an indirect, but significant, influence on air temperatures. However, because air mixes within the atmosphere, the relationship between surface and air temperatures is not constant, and air temperatures typically vary less than surface temperatures across an area (Figure 1) [153].

As highlighted by Massetti et al. [155], and recognized by many international studies, the concentration of population and buildings in a small portion of the territory alters its characteristics to the point of creating a local climate that is significantly different from the surrounding rural areas [156]. This effect modifies all meteorological variables but, especially, the wind regime, the distribution and intensity of temperatures, and urban water cycle. The urban heat island (UHI) is also influenced by the roughness of the surfaces, and by the materials with which they are built that modify the permeability and help to store energy and re-emit it in the form of sensible heat, rather than dissipating a part of it as latent heat due to the evaporation of water from the ground [128].

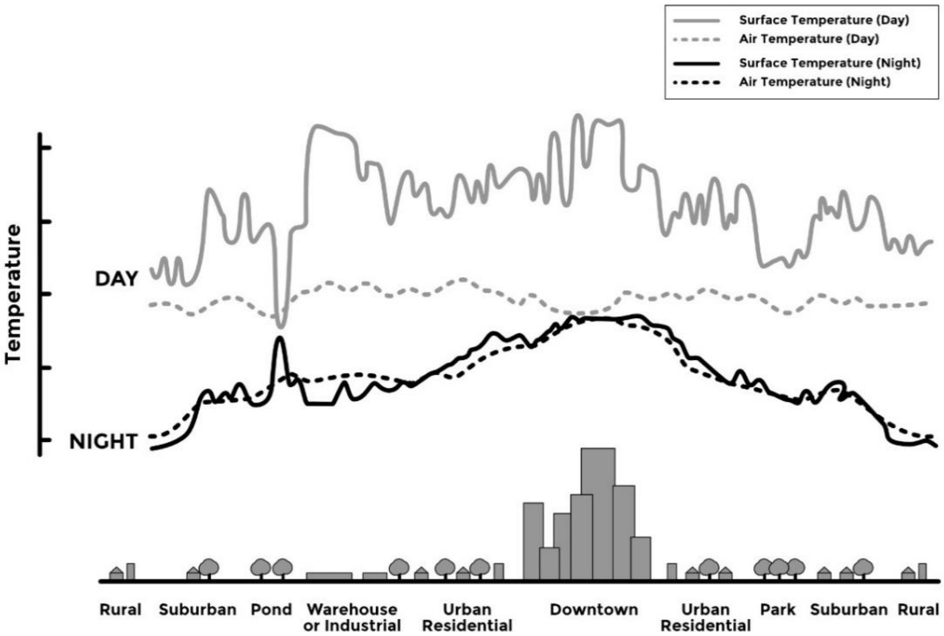

Figure 1. Relative changes in air and surface temperature during the day and night above surfaces with different designs. Temperatures fluctuate based on factors such as seasons, weather conditions, sun intensity, and ground cover. Source: Environmental Protection Agency (EPA, 2008).

In the climate change context, extreme atmospheric events can have significant consequences on the urban environment and on the resident population and one of the most important problems concerns the frequency and intensity of heat waves [157]. These effects are clearly highlighted by various indicators, such as an increase in working days lost due to illness and an increase in calls to emergency numbers on the hottest days [158], but also to a greater mortality rate for elderly people in conjunction with extreme events [159–163].

Therefore, the issue of thermal comfort in urban environment becomes central when related to the health of the population. Green spaces that can offer conditions of thermal well-being or more pleasant temperatures than the average urban situation during hot summer days have an important positive effect on the health of the population [147,164,165]. Pielke et al. [166,167], for example, introduced the concept of surface air moist static energy as an alternative method to assess heat stress combining temperature and humidity showing that sometimes heat waves are less extreme due to very low humidity accompanying the event. This means that the knowledge of the urban climate and its peculiarities are a strategic area of study for planning future urban development. The international literature suggests the need for a greater understanding of the thermal dynamics that occur within cities [168,169] and the necessity to convey this information to urban planners and public administrations [170], so that they can use the information in order to make the urban environment more sustainable and to improve the well-being and health of citizens.

Vegetation cover can help to improve the climate and reduce energy consumption both at the micro and macro level. In terms of microclimate, the presence of plants around a building can significantly reduce the effect of solar radiation on the external walls and lower the energy costs necessary for air conditioning, which, in turn, entail a lower energy demand and a reduction of the environmental impact that buildings will have on the community [171,172]. Numerous studies have analyzed the effects of vegetation and green areas on the microclimate of the city [173–177]. Although there are some conflicting data on the effect of vegetation on air temperature, in general, the presence of green areas is considered as a factor that has positive effects on decreasing the temperature in an urban environment thanks to the shading effect on urban surfaces and on buildings and also to evapotranspiration (evaporation from the soil and transpiration by plants) that reduces the transformation of incident solar radiation into sensible heat in favor of latent heat [117,147,152,172,178–180]. Conversely, during winter, planting a barrier of windbreak species on the north side protects buildings from cold winds, reducing fuel consumption for heating. Thus, planting trees around buildings is not only a positive step towards reducing energy consumption, but also has a significant direct financial benefit.

The Lawrence Berkeley National Laboratory and the Sacramento Municipal Utility District showed energy savings between 7% and 47% for air conditioning costs, determined by the presence of trees around the houses. Trees planted on the west and south-west of the buildings produced the greatest savings [147,181]. The west side is the most important to shade in summer, through broadleaved species placed 3–9 m away from the building. To avoid unwanted shading effects in winter, it is preferable to plant trees with late foliation and early abscission, avoiding species that keep dry leaves in winter (i.e., hornbeam and oaks). Actually, some species, despite being sparse, do not drop their leaves in autumn, but in late winter or even immediately before the new leaves are produced in spring.

Finally, tree cover, as little as 20% of the surface, could turn into a reduction of 8%–18% for air conditioning and 2%–8% for heating [182]. The results of Loughner et al. [183] show that, in the considered urban areas, the addition of trees decreases the air temperature in an "urban canyon" of 4.1 °C and that of the pavement and walls of the buildings at 15.9 and 8.9 °C, respectively. The strategic planting of the trees around buildings is essential to reduce the incident radiation on them, hence their temperature. In fact, not only parks, but also single trees or single rows of trees can have positive effects on the thermal environment [184,185], especially if, as just described, they are planted in strategic positions [155].

Some of these studies have tried to quantify the energy benefits of the presence of trees near buildings mainly due to the reduction of the amount of incident radiation on the walls of buildings. Depending on the exposure of the shaded walls, it is possible to observe a reduction in the temperature of the walls between 5 and 20 °C [186–188], with consequent savings for air conditioning during the summer period of about 10%–35% [189,190], even reaching 80% in particular situations [191]. All this is reflected at the macro-scale level with benefits at regional or even higher levels which, as mentioned, also lead to significant economic savings.

Moreover, green areas are generally permeable surfaces and therefore they allow a higher water penetration into the ground, making it available for evapotranspiration and thus contributing further to the reduction in temperature. However, that in some situations there are no significant changes in terms of maximum air temperature between paved areas and green areas [192]; the same authors suggest avoiding parks with herbaceous vegetation alone in Mediterranean environments, as they do not produce tangible effects of mitigation of the air temperature, but can, instead, require maintenance costs and high water consumption. This statement can easily be refuted by simply stating that in Mediterranean areas or, in any case, in those characterized by a hot and dry climate during the summer season, the use of xeric species can greatly reduce water needs of green areas.

Other studies that have considered urban parks of a large size have shown that these are always characterized by lower air temperatures than the surrounding urban environment [175,176] and that their positive effect on the reduction of temperatures can also be expanded in the nearby urbanized environment [193], with a reduction in temperature that is most evident in the streets near the park, in the leeward part of the park [178]. Other experimental studies on the refreshing effect of parks have estimated a reduction in temperature due to the presence of parks, from 1 to 5 °C depending on the size of the park [188,194,195].

In Singapore, the maximum difference between the average temperature recorded outside a park and that recorded inside is approximately 1.3 °C [196], while in Mexico City it has been shown that a great urban park (about 2 km wide) can be 2–3 °C cooler than the urbanized area that surrounds it, and that the effect is measurable up to a distance from the park of about 2 km, corresponding approximately to its width [193]. Research conducted in China has shown that the presence of green areas even of limited size has significant effects on the values of temperature and relative humidity (especially in the early afternoon and summer). Compared to open non-tree-lined sites (used as a control), the temperature reduction due to plant communities ranged from 2.14 to 5.15 °C, and the relative increase in humidity from 6.21% to 8.30% [197].

The presence of vegetation in an urban environment is therefore strategic for the mitigation of the heat island phenomenon, but in order for the information to be correctly used by city planners and administrators, it is necessary to provide precise evidences on the type of vegetation to utilize and how it should be placed within the urban fabric [198]. In the United States, a nationwide initiative would produce savings of about $1 billion a year on heating and cooling costs, which means fewer fossil fuels burned, and less carbon dioxide emitted [199]. According to Bhargava et al. [200], the UHI effect can be mitigated, especially in new developing cities, by conceptualizing the urban planning following some simple concepts: (1) optimization of concrete to non-concrete urban surface areas through well-defined simulation models; (2) optimization of vertical to horizontal expansion of cities or urban areas through well-defined simulation models; (3) urban planning and development of green belts or green covers considering the aerodynamics of the region from the concept stage; (4) ensuring and maintaining the air ventilation of urban areas; (5) balancing albedo effect in urban area and by reducing of albedo factor of asphalt by application of high reflectivity coatings to asphalt and, above all, reducing soil sealing wherever possible; (6) installation of green roof in buildings in the urban area which includes development of plants and vegetation to harness evaporative cooling thereby restricting heat island; (7) planning and development of green buildings (i.e., a building that, in its design, construction or operation, reduces or eliminates negative impacts, and can create positive impacts on climate and natural environment) in the urban area.

8. Conclusions

Increasing urban green areas is one of the prerequisites of most environmental programs of the main international institutions that deal with the environment and, in the present scenario of global changes (not only climate change), the choice of plants to be included in our cities should not be done on aesthetic bases, but must take into account the potential environmental "contribution" that the species will be able to make in relation to maintenance costs. Therefore, it is of paramount importance to expand urban vegetation (since it is one of the most effective mitigation strategies for reducing the global change impact); it is also a priority to establish rules about where to plant (i.e., in urban parks, in peri-urban parks or mainly streets), what to plant (i.e., native or exotic species, varieties and cultivars, keeping in mind the importance of biodiversity), why plant (i.e., what are the reasons for planting? climate mitigation, pollution reduction, hide visuals, etc.), how to plant (i.e., concentrated massive plantations, scattered or widespread planting with the creation of ecological corridors and stepping stones), and also who should be in charge of planting and managing green areas (i.e., public institutions, volunteers, private owners, etc.). These choices should be based on parameters such as proportion of pollutants removed, daily emission of volatile organic compounds, production of pollen and allergens, effects on the mitigation of the urban heat island and on the energy efficiency in the neighboring area. All these factors must always be taken into account according to the principle, "the right plant in the right place and with the right management"; it is not enough that the plants survive, they must also have, for example, high rates of photosynthesis and growth and, consequently, a higher environmental contribution. Therefore, plant selection is one of the most important components in an effectively sustainable program to keep our cities healthy and thriving. Much work remains to be done, especially in determining the optimal arrangement of green infrastructures in the urban landscape, but there is sufficient information available to take positive, preventive actions to start mitigating climate change.

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