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Review

The Complex Issue of Urban Trees—Stress Factor Accumulation and Ecological Service Possibilities

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Abstract: This review paper is the first that summarizes many aspects of the ecological role of trees in urban landscapes while considering their growth conditions. Research Highlights are: (i) Plant growth conditions in cities are worsening due to high urbanization rates and new stress factors; (ii) Urban trees are capable of alleviating the stress factors they are exposed to; (iii) The size and vitality of trees is related to the ecological services they can provide. Our review shows, in a clear way, that the phenomenon of human-related environmental degradation, which generates urban tree stress, can be effectively alleviated by the presence of trees. The first section reviews concerns related to urban environment degradation and its influence on trees. Intense urbanization affects the environment of plants, raising the mortality rate of urban trees. The second part deals with the dieback of city trees, its causes and scale. The average life expectancy of urban trees is relatively low and depends on factors such as the specific location, proper care and community involvement, among others. The third part concerns the ecological and economic advantages of trees in the city structure. Trees affect citizen safety and health, but also improve the soil and air environment. Finally, we present the drawbacks of tree planting and discuss if they are caused by the tree itself or rather by improper tree management. We collect the latest reports on the complicated state of urban trees, presenting new insights on the complex issue of trees situated in cities, struggling with stress factors. These stressors have evolved over the decades and emphasize the importance of tree presence in the city structure.

Keywords: abiotic stress; soil compaction; particulate matter; light pollution; ecological service

1. Introduction

The transformation of natural and agricultural lands into urban areas is increasing every year. It is estimated that 66% of the world's population will live in cities by 2050, compared to 30% in 1950 [1]. In those areas, humans, other animals, and plants coexist together. Dense buildings, heavy traffic, construction work with deep excavation, and the common use of concrete and glass materials leads to the degradation of the environment in relation to plant growth. Because of the dense buildings and limited space for root growth [2,3], as well as for upper branching, unfavorable factors occur at the same time, enhancing plant stress (Figure 1). Basic requirements for plants, such as soil, rainwater supply, air, and light are greatly modified in urban areas in comparison to rural conditions [4–7]. Due to the specific localization of growth, the terms of 'urban forests' and 'urban trees' have been distinguished. According to Escobedo et al. [8], an urban forest is the sum of all vegetation in a city area, including trees, shrubs, lawns and pervious soils. Following Roy et al. [9] an urban tree is "a woody perennial plant growing in towns and cities". They include "individual trees as well as those occurring in stands, patches and groups within publicly accessible green-spaces". Although the set of stress factors in cities impact all trees, individual growth stands differ in terms of their intensity. Trees exposed to urban stress factors at the highest intensity are roadside trees [10]. Their average lifespan is shortened in comparison to rural areas. Similar conditions affect trees growing on squares and in tree pits around the city. Park trees, which experience moderate stress, are less affected [10]. In this group, estate lawns and private property greenery around the city may also be included. Finally, urban woodlands are the least affected by urban stress factors. In such conditions, trees can achieve a final age similar to those growing in rural areas. The stress factors of trees in urban woodlots are related largely to climatic conditions, long term pollution and biotic damages [10]. What is more, because of the high number of citizens in a relatively small space, all green areas are highly used. Therefore, species selection needs to meet the criteria of the specific location of growth conditions, stress resistance, and also planned function. Urban greenery planners need to have in mind that, without proper growth conditions, trees cannot service ecological functions in a sustainable manner.

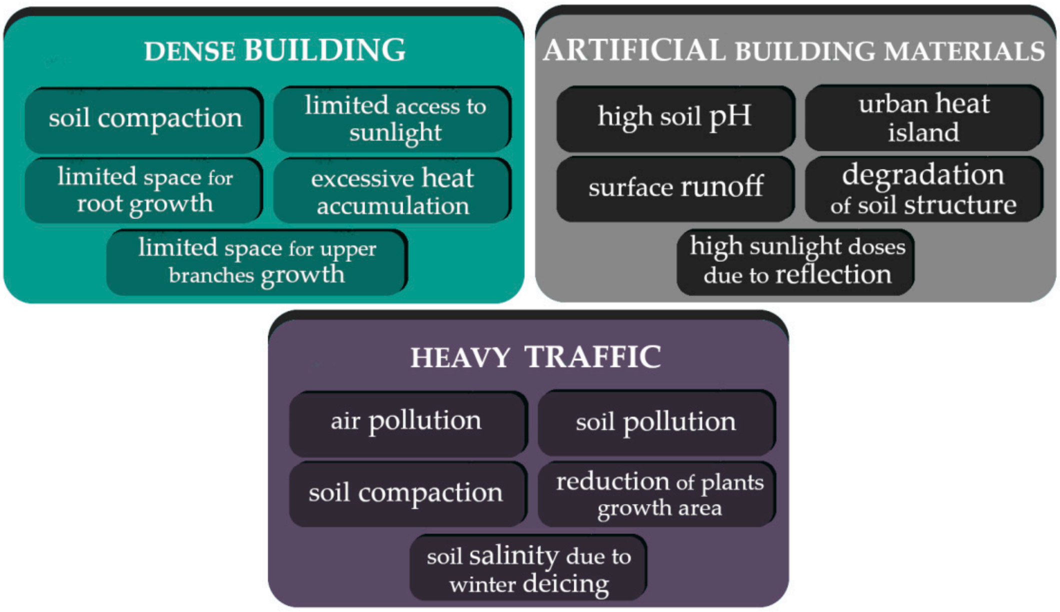

Figure 1. Sources of stress factors in urban conditions.

Access to water and mineral nutrients is a fundamental requirement for plant growth. The uptake of water occurs through the root system. Unlike greenhouse cultivation, in any landscape, plants are rooted in soil. Soil has many ecological functions, such as mitigating climate change, carbon absorption, water retention, and functions as an environment of microorganism growth [11,12]. However, soil transformation in cities leads to its degradation, which implies stress for plants. Because of all the modifications soil is subjected to, it is called anthropogenic or urban soil [13,14]. Such formations are highly heterogeneous, with irregular horizons and anthropogenic layers. The degradation of soil concerns physical and chemical changes. Critical changes include soil compaction, disturbing water–air relations, water shortages due to surface runoff, high soil temperature, salinity, pollution, increased pH, and also organic matter and mineral deficiency. These factors decrease microbial activity and soil enzyme activity, and finally deprive the service function of soil [15].

Another significant issue in relation to plant growth and development is air quality. Air temperature and composition (CO_2, O_3, NO_2, particles etc.) are modified in urban areas. These factors impact plant physiology, for example, photosynthesis or enzymatic activity [16]. Aside from these physiological impacts, poor air quality can impose mechanical changes, such as stomatal occlusion by dusts suspended in polluted air. Such changes result in the worsening of gas exchange and therefore disturb the vital processes of trees [17].

One more essential factor for plant functioning is light, which is the source of energy necessary for photosynthesis and information about the plant's environment. Equally important are light quantity (intensity), light quality (spectral composition), direction, and duration. Due to high, shade-giving buildings in the city area, there are changes in the light intensity reaching the leaves. Phases of light and dark in diurnal cycles can also be disturbed. While carbon assimilation needs a large volume of light quanta, photoperiodic control is sensitive to small light doses and diurnal changes. In highly modified urban areas, trees need to cope not only with both extensive lightning and light deficiency, but also with artificial light doses during the night.

In this review, we focus on urban trees growing in highly intense conditions in the presence of many stress factors—mostly street trees and those growing in other paved areas such as squares, tree pits, and planters. We provide information about the changes in and degradation of the environment for plant growth in urban areas. Our elaboration is based on the latest literature on the ecological benefits of trees in the city structure. Our goal is to present, in a clear way, the co-existence of stress factors affecting urban trees and the benefits that trees bring to cities. We develop a new multi-layered framework linking those two areas, and present how human-related environmental degradation can be alleviated by the presence of tree vegetation. As a background, we discuss subsequent environmental changes such as (i) soil degradation, (ii) air quality, and (iii) light condition disturbances. Using this framework, we outline how those overall changes affect tree dieback. Further, we investigate, in depth, the importance of trees in urban ecosystems, and present how degradation can be balanced by the presence of trees. Finally, we present some issues perceived by city dwellers as drawbacks of tree vegetation. In this sense, we argue they can be avoided by proper management.

2. Abiotic Stress Factors in the City Area

2.1. Soil Degradation

2.1.1. Soil Compaction

One of the major problems concerning anthropogenic soils is compaction. Compaction affects both soil structure and its functioning. This problem is caused by heavy traffic, common construction work, and dense buildings. Soil compaction is thought to be a substantial reason for tree mortality in cities. Due to the physical difficulties of root development and poor capillary movement in such formations, water absorption is reduced, which significantly disturbs assimilation processes and mineral uptake [18]. The reduction in soil porosity results in poor water and air permeability, lowered colonization by microorganisms, and a reduction in carbon absorption capacity [19,20]. A properly developed root system ensures the maximum uptake of water and minerals. It is especially important when access to water and nutrients is limited. Meanwhile, roots in dry and compacted soil grow more slowly, both due to water stress and mechanical resistance [21]. Limited root growth space reduces water uptake, even if optimal irrigation is provided [22]. Studies conducted on 22 plant species with optimal irrigation revealed that in heavily compacted soil, root elongation was reduced by more than 90% compared to plants growing in vermiculite [23]. In addition, studies conducted on *Eucalyptus albens* showed an inverse linear relationship between bulk density and root growth. The depth of root penetration through the substrate decreased when soil bulk density increased [24]. In a study conducted in Germany, roots of 20- to 40-year-old *Tilia* ssp. trees were exposed to investigate the underground factors affecting root growth and development. Root development was inhibited by layers of clean sand, gravel, and compacted loam layers. Better root development was observed in irrigated areas and where coarser fractions of gravel and debris were mixed with finer fractions of clay and silt [20]. An extensive and properly branched root system has a better chance for survival in difficult conditions. Limited water availability in urban soils can result in deeper rooting. Such reactions often result in damage to urban infrastructure, such as pavements, foundations, and pipes. Under natural growth conditions, between 60 and 90% of the roots are in the topsoil, which is about 20-cm deep. Structural anchor roots reach a depth of about 60 cm [25]. Ground penetrating radar was used to map the roots of *Quercus phellos* and *Q. bicolor* in New York over a 17-year period. Trees were planted in structural soils in two groups: in the sidewalk (12 *Q. phellos* and 14 *Q. bicolor*) and in a lawn (17 *Q. phellos* and 19 *Q. bicolor*). The roots of trees were analyzed with ground penetrating radar nine times, beginning two years after installation. For both species, approximately half of the roots under the pavement were located at a depth of 21–42 cm [26]. In manmade environments, roots cannot expand in the upper layer (about 20 cm) as they can in natural conditions. A deeper root location implicates poorer water access and also gas exchange. Poor water–air relations in such media are another limitation for the development of roots in compacted soil. Studies carried out on pine seedlings have shown that reducing the oxygen and water content in compacted soil can reduce root growth by up to 33% compared with the control [27].

2.1.2. Soil Drought

Reduced soil moisture in cities is associated with surface runoff, poor water retention, and climatic drought. One of the main reasons for this process are anthropogenic activities, such as urbanization and deforestation. Although, there are many factors influencing the intensity of this process, such as land use, land cover, or river networks, the problem is more alarming because of floods that are predicted due to climate change. Cities are more prone to devastating floods because of poor rainwater distribution [28], due to the high coverage of impermeable surfaces (hardscapes) such as sidewalks, asphalt, curbs and gutters, which act as barriers to the infiltration and concentration of water [29]. Increased surface runoff is associated with a loss of rainwater in urban areas, which has consequences not only for plants, but also in increasing the cost of sewage infrastructure [30]. It is estimated that surface runoff from impermeable areas, such as asphalt or concrete, is 10–20 times greater than from lawns. In general, in heavily built-up areas, the loss of rainwater can reach up to 50% or more, while in forest areas it is often less than 5% [31]. Soil drought affects phenology, growth and also the morphological development of urban trees [32]. Trees growing under drought conditions have accelerated leaf coloration and leaf fall in autumn [32,33]. Long term drought negatively affects the radial growth of urban trees [34]. It also significantly decreases the maximum net photosynthesis, as presented for *Fraxinus chinensis* and *Ginkgo biloba* growing in paved areas [35].

2.1.3. Extreme Soil Temperatures

Root growth may also be disturbed by high soil temperatures. It is assumed that for temperate-climate plants, the optimum soil temperature for root growth is up to 25 °C, depending on the species [20]. An elongation of growth in many species is inhibited at temperatures below 10 °C [20]. At an ambient air temperature of 33.5 °C, the temperature of the pavement can reach up to 55 °C in a place with full sun exposure and 37 °C when the pavement is shaded by the crowns of trees. At the same time, the temperature of grass shaded by trees in these conditions reaches a temperature of 27 °C [36]. The maximum difference between asphalt and grass surface temperature measured in an experimental study in Japan was 20 °C [37]. The soil temperature under asphalt can be up to 16 °C higher than at the same depth below the lawn [38]. This suggests that the roots of trees growing under impermeable surfaces such as asphalt would be more prone to extreme temperature stress than those of trees growing in lawns. The color of the materials used to build the surface surrounding the vegetation is also of great importance. Asphalt surface temperatures can be up to 15 °C higher than the air temperature, with the difference for light-colored materials being around 7 °C [39]. High soil temperatures may cause a range of planning impacts: the inhibition of root growth, death of root tips, disturbances in the uptake of minerals and water, poorer colonization by beneficial microorganisms, increased colonization by pathogenic organisms, and changes in respiration intensity [20,40,41]. Moreover, extreme temperatures in soil can negatively affect photosynthesis and the relative water content of leaves [42]. Soil temperature can also generate stress conditions in the winter. In the natural environment, during cold winters, the soil is frozen, and water is not available for the roots. Meanwhile, in the city space, a dense network of underground pipelines changes the temperature of the soil, leading to thawing [43]. In such conditions, the winter dormancy of plants may be disturbed.

2.1.4. Contamination, pH Changes, Nutrient Deficiency

During construction work, heavy machinery leads to the mixing of soil horizons with materials such as steel, aluminum, concrete, and cement [15]. Particles affecting urban soils are not only organic and mineral, but also include artificial and processed materials. The major source of these particles are fertilizers from areas cultivated nearby, household waste, weathering products for building materials, construction waste, low-particle dust emitted by households, and transportation byproducts, such as fuel combustion products or the abrasion of vehicle parts. Soil pollution has been documented along roadsides in cities all over the world, including China [44], Brazil [45], India [46], Russia [47], Iran [48], Turkey [49], Australia [50], Italy [51], Germany and Poland [52], among others. This underlines the large scale of the problem. The differences in the level of soil pollution between cities are affected by many factors, such as the distance from the source, the length of exposure, the content of organic matter, and soil pH [53,54]. In addition, the modernization of engines and fuels reduced the emissions of some pollutants, often in favor of new, less researched ones. For example, the replacement of lead catalysts in favor of platinum resulted in an increase in soil pollution with this element [55]. Contamination with platinum is therefore a new stress factor appearing in cities. Nitrogen and sulfur oxides emitted by transportation react in the atmosphere with water vapor, and then return to earth as acid rain. The release of heavy metals, the leaching of nutrients, and the sterilization of already poor urban soils are the most important effects of such modified precipitation [56]. Another stress factor of urban soil is its salinity. As a result of the high use of de-icing agents in the winter, cities struggle with the problem of contaminating roads with the ions of used salts. These ions get into the soil from the melting snow and salt spray dispersed while driving cars, as well as from dust deposited on the road surface [57]. Salt contamination of soil inhibits water uptake, root growth and also damages root cells depending on species sensitivity, environmental factors and stress duration and severity [20]. Two types of stress are observed in the case of root salt contamination: osmotic stress related to disturbances in water uptake and ionic stress connected to specific ion toxicity in the tissue. Salt stress also affects the colonization of tree roots by mycorrhizal fungi [20]. Studies of roadside soils showed their toxicity to living organisms and were also associated with damage to the leaves of the studied lime trees (*Tilia cordata*); necrotic changes reached up to 60% on the surface of leaf blades [58]. The effect of salinity on the condition of roadside trees where NaCl, $CaCl_2$, or $MgCl_2$ were used as deicing agents was investigated. Melting snow significantly affected soil alkalization and increased the presence of chlorine ions in the soil. In addition, leaf abortion and a reduction in tree vitality was observed in plants growing closest to roads with heavy traffic [59]. Notably, soil salinity has also been associated with sooty mold leaf damage [60]. Another issue is the salinity source and dose, for example, $CaCl_2$ is typically less toxic for plants than NaCl. However, in high doses, both deicers significantly decreased the physiological performance of *A. saccharinum* seedlings. The highest salt doses induced proline content and increased superoxide dismutase SOD activity in treated maple seedlings [61]. Chlorophyll content in the leaves of silver maple seedlings was not affected by salinity treatment. Contrasting results were described in four different tree species growing in boulevards and along streets in Edmonton, Canada. High soil electrical conductivity EC with increased Na^+ concentrations was related to decreased chlorophyll content in comparison to control locations [62]. This investigation revealed that Na^+ concentrations were relatively high, even up to 50 m from the main road. Authors also underlined the necessity of complex approaches to salinity stress, concerning soil salinity and airborne deposition, as well as salt concentration. The huge differences in salt tolerance between species emphasize the importance of tree planting sites and species selection [62].

The widespread use of limestone materials in cities also contributes to changes in the pH of urban soils that deviate from the optimum for most plants. At a high soil pH, some minerals occur in insoluble forms, making them unavailable to plants. In addition, soil alkalization may affect the existence of mycorrhizal fungi [20]. Limiting the occurrence of this group of microorganisms is also caused by unfavorable soil conditions, such as mineral deficiency, pollution, and drought. The symbiosis of tree roots with mycorrhizal fungi is particularly important in cities, affecting both soil structure and the availability of mineral compounds and water [63].

The high road density in cities is associated with soil contamination, with various transport-related substances, such as heavy metals and polycyclic aromatic hydrocarbons (PAHs), among others [64,65]. Recently, traffic-related pollution has been linked not only with fuel combustion, but also with tire and road wear particles (TRWP) [66]. This is another stress factor that increases with intensified traffic. In the composition of these particles, there are PAHs and metals: Si, Zn, Al, Ca, Fe, and Mg [67]. Car tire tread wear is a source of Zn, Mn and Ni, wear of the braking system is associated with Cu and Ba emissions, and brake linings are associated with Mn and Sb emission [68–70]. Together with exhaust emissions from engine fuels, the consumption of car parts and roads provides a mixture of dusts of various compositions, which contribute to soil pollution. Soil contamination by excess amounts of heavy metals can cause the inhibition of root growth (disturbances in cell division and cell elongation), increased cell membrane permeability, changes in metabolism and the production of reactive oxygen species [20]. A restriction in root growth negatively affects shoot growth and development. Some morphological changes can also be observed, like injury to the root apex, changes in root branching or the inhibition of root hair formation.

2.2. *Air Quality*

2.2.1. Air Temperature

Air temperature is another environmental factor that changes as a result of urban development. While global warming has resulted in a global air temperature increase of 0.7 °C since 1900, the temperature rise in urban areas is noticeably higher [16]. The increase in the average annual temperature in the city center and the associated decrease in relative humidity is referred to as the urban heat island [71]. The difference between rural and highly urbanized areas such as Singapore and Mexico City reached up to 4 °C in summer [72]. Due to the high heat capacity of materials used in a city, such as concrete, asphalt, sheet metal, etc., heat is accumulated during the day and slowly released at night [73]. In addition, as a result of leaks in buildings' heating networks, "heat leakage" is observed [74]. Furthermore, the effect of heat waves in cities influences trees' physiology, as well as their growth and development, especially when accompanied by high light doses and drought. For most species, the optimal temperature for photosynthesis is between 20 and 30 °C, and even up to 35 °C where high photosynthetic rates are maintained [75]. Elevated temperatures promote respiration rates; therefore, they can be linked with higher net CO_2 emissions [76]. As described for *Populus tremula*, there is a temperature breakpoint, from which a further increase is linked with a faster rate of respiration increase. In an experiment conducted on four-year-old rooted cuttings, the break point was about 46 °C. Respiration rates at the highest temperatures (about 52 °C) exceeded the values measured at 22 °C by 10- to 14-fold [77].

Due to the high frequency of periods of excessively dry air in cities, the term urban dry island is found in the literature [78,79], and it is considered as one of the new stress factors. This phenomenon can alleviate the perception of heat waves and sultry weather by city dwellers [80], while in plants it causes the closing of stomata and therefore reduces photosynthesis and transpiration [81]. However, up to a certain point, an increase in air temperature enhances transpiration, which, in turn, contributes to soil drying. In the urban environment, increased temperatures and decreased humidity result in an increased vapor pressure deficit (VPD) in the air, which affects the transpiration rate of urban trees [82]. A positive relation was also found between transpiration rates (daily and hourly) and VPD. Moreover, stem growth and photosynthesis can be inhibited by increased VPD [83], which is correlated with decreased stomatal conductance. A strong negative correlation between growth rate and VPD was observed in *Tilia cordata* plants [84]. A positive correlation between VPD and daytime sap flow was also reported [85]. All these findings indicate that high VPD with soil drought may cause growth cessation, photosynthesis inhibition, wilting and even mortality [86].

2.2.2. Air Pollution

Air in urban spaces is also heavily polluted, both by transportation, industry, and households. Gaseous pollutants are mainly direct combustion products, such as SO_2, CO, and NO_2, formed in the atmosphere as a result of the transformation of directly emitted pollutants [87]. Additionally, gaseous carcinogens, such as polycyclic aromatic hydrocarbons (PAHs), are present in the urban air. All combustion processes occurring in the city produce fine particles called particulate matter (PM) [88]. Street canyons, where tall buildings are located on both sides of the road, disturb air circulation and such conditions intensify air pollution [89]. While the accumulation of PM by tree leaves is favorable for urban citizens, it has negative effects on plant functioning. The exposure of trees to high PM levels is connected to a lower relative leaf water content and photosynthetic pigments (chlorophyll and carotenoids) [90]. In urban conditions, the CO_2 content is also increased. It was estimated that, in 2018, total world emissions grew by 2.0% with an annual growth rate of 1.0% in the period of 2007–2017 [91]. The short-term effect of elevated CO_2 in the air is connected to higher photosynthetic rates. However, acclimation to the long-term exposure to such a change causes reduced photosynthetic stimulation. Furthermore, this effect can be increased while plants grow in small restricted areas and with nutrient deficiencies, as takes place in cities [16].

2.3. Light Condition Disturbances

2.3.1. Inadequate Light Doses

In urban conditions, the supply of light energy is modified in various ways. To reduce the heating of building materials used in the city, it is increasingly recommended to use materials with a high albedo [92]. As a result of the large proportion of surfaces that effectively reflect solar energy, the excessive illumination of plants may occur. This may lead to photoinhibition, sunburn, and ultimately to photosystem II (PSII) damage [93]. Moreover, the effect of light intensity is modified by drought stress. The deficiency of water enhances high light stress reactions and photosynthesis disruptions in trees [94].

High buildings shadow trees growing close to them, disrupting access to radiation. In densely built-up parts of the city, street trees or those growing on small squares may have limited light access throughout the day [95]. Photosynthetically active radiation (PAR) in the shade of buildings can be reduced by up to 50%, compared to trees grown in full sun exposure [96]. The study conducted in Singapore included two different green community areas with high-rise buildings around them. Continuous measurements with 5-min intervals were taken on these sites for about one month. As a second part of the study, chlorophyll fluorescence was measured to determine the photosynthetic capacity of leaves at different PAR levels. It included a total of 35 species of trees and shrubs and did not show a drastic deterioration in photosynthetic efficiency with decreasing PAR access. Significant changes were noted only in four species of shrubs and in two species of trees with a greater slenderness factor, suggesting a lack of light [96]. In contrast, research conducted in Fukuoka, Japan, on the *Ilex rotunda* showed a higher photosynthetic performance (P_{max}) under low PAR. The authors emphasize that the conditions of reduced radiation prevent photoinhibition, which could have affected photosynthesis [97]. Different results were obtained when testing *Liquidambar styraciflua* in a street canyon in Washington. Reduced radiation as a result of shadowing by tall buildings caused a reduction in photosynthesis [98]. It should be emphasized that *L. styraciflua* is considered photophilous, while *I. rotunda* is tolerant of shady conditions. The appropriate selection of tree species can therefore change potential stress factors into positive conditions. Specific light conditions occur in street canyons, which are common in urban structures. In such areas, daily radiation is modified, dependent on the east–west position. Because of shading, carbon assimilation and stomatal conductance were decreased in *E. olivacea* and *O. europaea* growing in the shaded side of a street canyon [99].

2.3.2. Artificial Light Pollution

The problem of light pollution at night is receiving increased attention in the literature. Light pollution is increasing with progressive urbanization, especially around large cities and road networks. Light emitted by street and pavement lighting is often distracted or reflected [100]. The light that escapes can interfere with plant photoperiod responses, affecting the perception of day length, as well as interrupting dormancy. Research carried out throughout Great Britain on four species of deciduous trees (*A. pseudoplatanus*, *Q. robur*, *F. sylvatica*, *F. excelsior*) showed the effect of artificial lighting on the timing of bud burst. The buds of the studied trees burst up to 7.5 days earlier in places with the highest light pollution in relation to the darkest places [101]. Moreover, blue light, which is used in cool light-emitting diodes LED lamps, speeds up the springtime bud burst by up to 6 days in *A. glutinosa* and *Q. robur* (in comparison to LED light without blue emission) [102]. Furthermore, autumnal phenophases can be disturbed by light pollution. The effect of blue light on the delay of bud set and leaf senescence has been investigated for different plant species [103]. The start of autumn phenophases can be delayed by up to 22 days in trees growing in the direct vicinity of a streetlight [104]. Earlier leaf unfolding and late leaf senescence could be beneficial due to longer photosynthetic efficiency; however, it could also expose the leaves to frost incidents and injuries. Disturbances in dormancy can therefore make whole plants more prone to critical frost damage [105]. Aside from phenological changes, plant physiology is disrupted by the duration of light exposure. *Liriodendron tulipifera* subjected to night light treatment showed reactions to stress, such as chlorophyll degradation, lipid peroxidation, and electrolyte leakage [106]. Night lighting can also affect nighttime transpiration. During natural darkness, the values of this process are low enough to support a recovery from wilting related to high transpiration rates during the day [107]. However, relatively small light doses stimulate stomatal opening and higher light intensities stimulate this process [108,109]. In view of this fact, light exposure during nighttime can enhance transpiration and therefore lead to greater water uptake, which is highly limited in urban areas. A scheme of the effect of artificial light pollution in comparison to the natural diurnal cycle is presented in Figure 2.

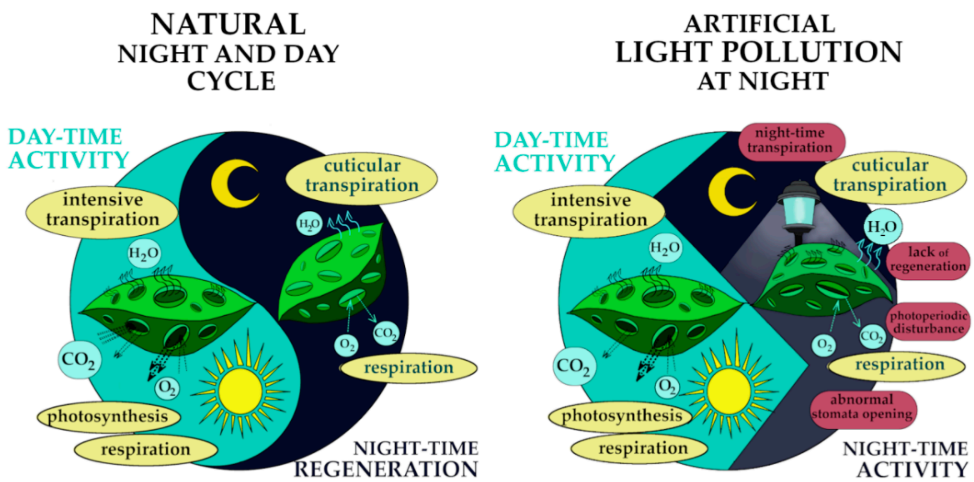

Figure 2. Natural night and day cycle and plant functioning disruption during artificial light pollution at night.

3. Tree Dieback in Urban Areas

In cities, growth conditions are constantly changing. Stress factors are, therefore, heterogeneous and change in intensity over the years. As a result of frequent construction work, the structure and properties of soil change and the roots of existing trees may be damaged [110]. The regeneration process of roots damaged by sidewalk replacement is species dependent [111]. During the development process, the density of trees decreases [112], which has an impact on the local microclimate. With changes in land cover, light, and water access, as well as air and ground temperatures, adjustment to changing conditions is extremely difficult. Additionally, for newly planted trees previously growing under optimal conditions in a nursery, almost all factors affecting growth and development are modified at the same time. For this reason, many young trees planted in urban areas with a high intensity of stressors die within a few years after planting [113]. A 10-year experiment in Boston showed that the average annual mortality of young trees is 3–38%, depending on the planting company. In Oakland, during two-year observations, it was estimated that the average annual death rate of newly planted trees was 19% [114]. In Helsinki, about 30% of newly planted trees must be replaced within a few years after planting [115]. A road report prepared for Berlin showed that the condition of the youngest roadside lime (*Tilia* ssp.) trees had deteriorated, which was not observed in the case of older trees in the same period [116]. Data on the maximum age achieved by urban trees found in the literature are varied. This is caused, among other things, by the diversity of urban tree growth location. The mean life expectancy of urban trees growing under high stress is less than 30 years [117]. This indicates that trees planted in urban areas die faster than those in rural areas. It is estimated that trees growing in residential areas, where "urban stress" occurs at the lowest intensity, can reach up to a 96.2% annual survival rate [118].

Shortly after planting, trees often experience stresses associated with changing the place of growth ("post-transplant stress"). The period of admission of the tree, after which an increase in the growth rate is noted, may last several growing seasons. Studies conducted on different tree species (*Acer campestre*, *Platanus acerifolia*, *Quercus rubra*) have shown that this period can last from 2 to 6 years [119]. Many more trees survive the stress period immediately after planting in areas where the public is involved in caring for greenery. Conversely, areas with low socioeconomic status showed a high percentage of tree dieback and the observed increase in dieback correlated with the level of unemployment. A study in three cities in California and Philadelphia, where the local community was involved in planting care, showed a surprisingly high percentage of tree survival. The correct selection of species for habitat conditions and community involvement allowed a more than 98% survival rate 6 years after planting the trees [120]. The main factors affecting the survival of newly planted trees are the attributes of the tree, the biophysical environment, people and institution involvement, planting time, and mulching practices [121]. A rarely mentioned aspect regarding the degree of tree survival is the quality of the nursery material and its proper preparation in the nursery. Trees hardened for stress conditions at the production stage have a better chance to cope with the extreme conditions prevailing in a city. In heavily used areas with high traffic or pedestrian activity and low expenditure on care, a high percentage of new plant dieback is recorded. The highest percentage of dieback is observed in areas related to transportation and industrialization. In these areas, damage in connection with transportation and vandalism is more common, while soil compaction is also greater. Some trees need to be removed before their death to prevent possible damage. Sometimes, trees in good health are removed because of human preferences or land use changes [122]. For European countries, the number of newly planted trees destroyed as a result of vandalism reaches about 5% in Central Europe in total and up to 30% in Great Britain [123]. Notably, studies carried out by Hamzah et al. [124] showed that tree position, value, and health had an impact on the likelihood of vandalism. This provides a chance to limit vandalism incidents with proper planning. In addition to damage as a result of vandalism, a major problem in cities is improper cutting during care treatments. In practice, excessive and radical "care" cuts are often encountered in practice, which lead to the significant weakening of trees [125]. In an inventory along four main streets in Warsaw, street plantings were analyzed 34 years after planting at a given site. On one of the investigated streets, as many as 70% of trees died from the 766 trees inventoried from 1973 to 2007. During this period, the city lost 64% of the planted *Tilia* 'Euchlora' trees, 65% *Tilia cordata*, 58% *Tilia platyphyllos,* and as many as 90% of the planted *Acer saccharinum*. On the second street, 94% of the planted *Sorbus aucuparia* trees died; of 51 items inventoried in 1973, only four remained after 34 years. On the third investigated street, 70% of all trees died in the examined period, with only 39% of the dominant species, *Acer platanoides*, surviving [126]. A scheme of the most common stress factors in relation to urban street tree dieback is presented in Figure 3.

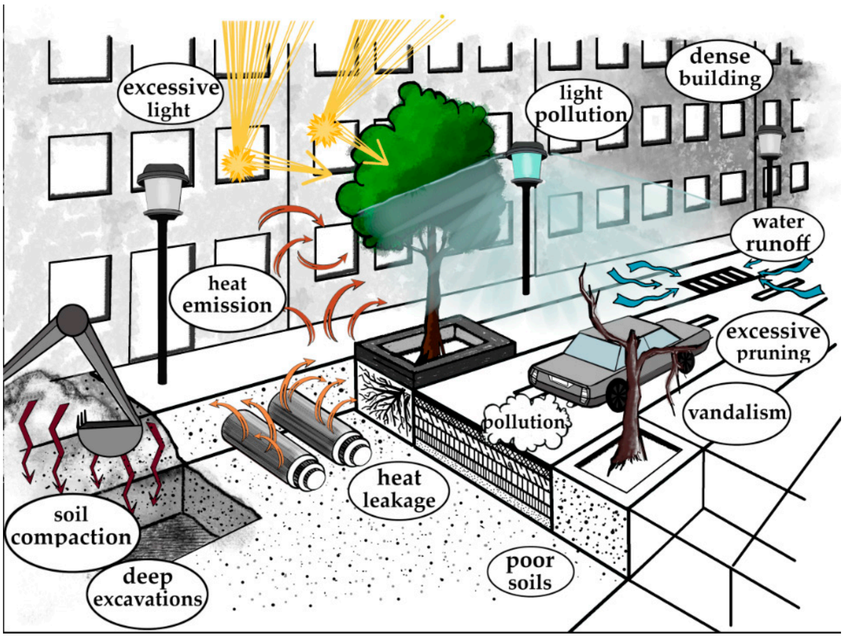

Figure 3. Most common stress factors for urban street trees induced by anthropogenic activity.

4. Importance of Trees in Urban Ecosystems

The presence of trees alleviates almost every stress factor generated by the urban environment. (Figure 4). These factors not only influence deteriorating plants, but also human health. Properly functioning and sufficiently large tree plantings can therefore improve the quality of citizens' lives. It is important for city dwellers and administrators to increase tree plantings. Trees regulate rainwater runoff, alleviate high greenhouse gas emissions, improve air and water quality, and reduce the urban heat island effect. At the beginning of the development of most cities, their environment was not as degraded as it is now. As cities become more urbanized, the benefits of tree planting become more important.

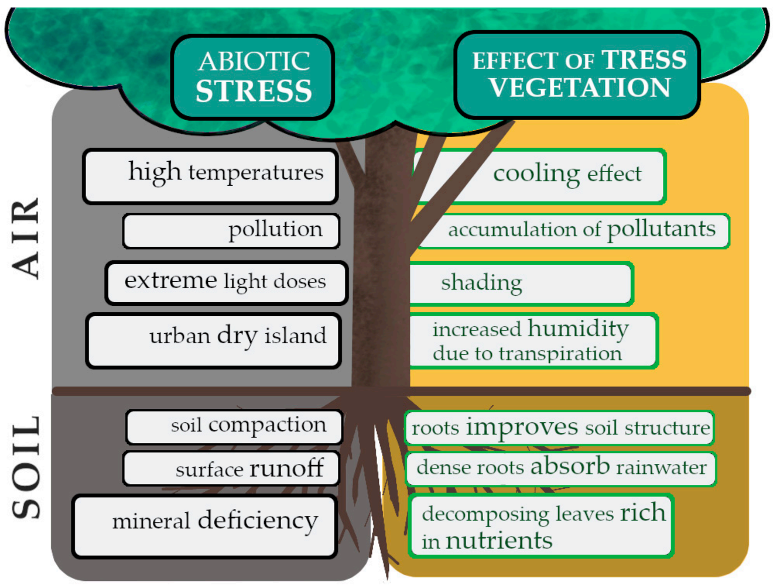

Figure 4. Abiotic stress factors occurring in cities and the potential of trees to alleviate them.

4.1. Changes in Perception of Urban Trees Role in History

The role of urban trees has changed over the centuries, such as the awareness of the numerous benefits that they bring. At the beginning of the development of civilization, trees were treated mainly as a source of food and building or raw material for energy. Public parks and their role in recreation were already known in ancient times [127]. However, city environments in those periods were much closer to nature than the next generation of centuries. In medieval times, the forest began to be cultivated for hunting purposes, which was a source of both food and entertainment for the upper classes. There is also some evidence of public park construction during this period. At the turn of the 17th and 18th centuries, the functions of forests began to be seen as recreational by a wider audience. Many royal parks and forests were opened to the public. Moreover, more attention was paid to their protection and they were even described as city treasures [127]. During the industrial revolution, the expansion of cities resulted in increased wood production. However, an increasing number of residents began to use the nearby forests as a place to rest and relax. Initially, it was widely believed that the function of forests in the city was limited to spiritual hygiene, and no real financial benefits associated with trees were taken into account [127]. In recent years, the function of urban trees has changed. They are no longer only ornamental or a source of raw materials, as they also provide measurable environmental benefits. In the nineteenth century, parks began to be set up to reduce pollution and prevent floods. In 1970, the term "urban forestry" was created in the United States to refer to tree management in an urban environment. Since then, the benefits of urban trees have been analyzed in detail [128]. Currently, the benefits of the presence of "green infrastructure" are referred to as ecosystem services. It is known that trees bring benefits for the mental and physical health of urban residents, but they can also bring socio-economic benefits [129]. The benefits provided by trees are divided into biophysical ones, such as better rainwater management, carbon dioxide sequestration, energy saving, the improvement of air quality, and non-biophysical benefits, such as improving the health of urban residents or reducing crime [130].

4.2. Social Benefits

Trees provide a wide range of visual stimuli. Leaf development, flowering, fruiting, the shape and color of leaves, shoots, and crowns change throughout the year. All these elements affect the aesthetic and visual value of the landscape [131]. Cultural benefits resulting from the use of urban greenery also include the need to connect with nature and extend the time of social meetings with family and friends [132]. The influence of trees on aesthetics, calmness, and spiritual feelings is difficult to valorize. However, scientists are attempting to develop tools to assess the impact of greenery on such feelings [133]. However, there is a concern that the greenery around houses may provide shelter or make it easier for potential criminals to reach higher floors. Research conducted in Portland, Oregon, USA, over the years 2005–2007 showed a relationship between the size of trees and the impact on criminal activity. Small trees, impeding visibility, were associated with increased crime, while the presence of large trees was safer [134]. A comparison of crime rates for 98 locations in Chicago showed that, in neighborhoods with greater green area coverage, crime is lower [135]. However, the reason for such a result might be more complicated than mentioned, as the direct influence of greenery on reducing crime is still under study [136,137]. In addition, the presence of trees along roads comprehensively affects the safety of car drivers and pedestrians. Trees not only provide a physical barrier between pedestrians and cars, but also allow drivers to realistically estimate the distance and adjust their speed to the conditions. Views of greenery during driving reduce stress for drivers therefore reduce the risk of collisions [138]. Research shows that the higher presence of greenery at home, as well as more street trees, is associated with lower stress, measured by cortisol levels and self-reported stress recovery [139,140]. Additionally, in experiments carried out in virtual reality, grass and tree environments showed a greater stress reduction than concrete-only environments [141]. Research conducted in California in 2003–2009 confirmed the beneficial effect of greenery on the health of residents. The health status of 4823 adults was analyzed, while assessing their place of residence in terms of vegetation coverage. Greater surface coverage with trees had a positive effect on overall health, regardless of whether the area was open to the public or closed. At the same time, the inhabitants of these areas also had a lower incidence of type 2 diabetes, asthma, hypertension, and fewer cases of obesity [142]. It is worth emphasizing the results of research conducted in the Netherlands, which showed that the health of residents is influenced not only by the amount of greenery, but also by its quality [143]. Proper planning and care practices maximize the benefits of urban plantings for urban citizens.

A valuation of the benefits of planting trees is difficult and complex. One part of the measurable benefits is the increase in property prices near green areas. Research conducted in Australia showed that an increase in the number of trees in a real estate area significantly affects the value of properties. Increasing the number of trees by 10% resulted in an increase in property prices by about AUD 2500 [144]. A modeling study in Western Australia showed that the presence of broadleaved street trees in a neighborhood of properties increased their price by about AUD 16,889 [145].

4.3. Soil

The influence of trees on soil is considered in several aspects such as ecological functions, structure, and retention capacity. The presence of soil in the city is associated with the different types of vegetation. In such extensively used areas, there IS no exposed land with bare soil. Therefore, the benefits of the soil itself are indirectly related to the presence of trees. An analysis of soil in 41 parks in Finland compared to forest areas showed an increase in THE accumulation heavy metals. The decisive impact on the mobility of these elements to the deeper layers of the soil were related to the humidity of the ground and the amount of water flowing through them [146]. In addition, trees also showed the ability to collect and accumulate pollutants of various origins. Research conducted on various tree species growing in contaminated soils, including urban soils, showed the potential for the uptake and accumulation of Cd, Zn, Cu, and Pb in plant leaves [147,148]. An experiment conducted under controlled conditions on two tree species (*Populus fremontii* and *Pinus ponderosa*) showed that soil–root interactions significantly increased the absorption and decomposition of organic carbon in soil. The carbon distribution in the rhizosphere environment was up to 200% higher than in the soil itself [149].

Widely growing roots stabilize the soil structure, prevent erosion, and improve the soil structure by creating micropores, which facilitate water infiltration deep into the soil profile. Conversely, due to the water needs of plants and water consumption during transpiration, greenery can reduce the amount of water available in the soil [150]. Improving the soil structure is associated with limiting surface runoff. Water runoff is significantly reduced by vegetative surfaces compared to paved surfaces, such as asphalt, with an up to 60% reduction for small trees and up to 99% for lawns [151]. In an experiment carried out in Great Britain, trees planted in 1 × 1 m pits surrounded by asphalt on an area of 3 × 3 m reduced surface runoff by up to 60% compared to a 3 × 3 m asphalt surface [151]. Trees reduce the escape of rainwater in several ways. In addition to the impact of roots on improving soil structure and reducing compaction, trees affect the water cycle by storing water in the tree crown [152]. Trees are a promising tool to fight water runoff in cities. According to the New York Municipal Forest Resource Analysis [153], one tree catches nearly 6000 L of water a year. However, these abilities depend on the size of the leaves and the crown surface.

4.4. Urban Microclimate and Air Pollution

A tree's ability to reduce air temperature brings significant benefits to residents and improves their quality of life. This cooling effect is achieved due to the reflection of light from the crown surface, as well as through transpiration. The shade given by trees protects the surface of pavements, roads, and walls from light and reduces heating. The cooling effect of trees depends on the size, shape, and architecture of the crown. The transpiration of tall plants in parks reduces the air temperature by up to 0.5–4 °C, depending on the type of park, its size, and the climatic conditions. As numerous studies confirm, cooler places on the city's thermographic map are associated with green areas. Research conducted in Germany confirms that even a few trees significantly affect the urban environment and can successfully reduce heat in cities [154]. In Melbourne, temperatures were compared in street canyons planted with different numbers of trees. The presence of trees in this type of urban area reduced the air temperature by up to 0.9 °C, improving the thermal comfort of people (Human Thermal Comfort (HTC)) [155]. A study conducted in Italy revealed that, depending on the ground structure, tree shadows can cool asphalt, porphyry, and grass by up to 16.4, 12.9, and 8.5 °C, respectively [156]. A new parameter of temperature, mean radiant temperature (Tmrt), has been evaluated to describe thermal comfort in a more complex way. It is derived from the area of urban human biometeorology and describes the radiation heat load. It is thought to be the main reason for summer outdoor heat stress and is more suitable than near-surface temperatures [157]. Studies in Hong Kong showed that large trees with short trunks and a dense canopy can reduce the average daytime mean radiant temperature (Tmrt) by up to 5.1 °C at the pedestrian level [158]. Research conducted in Gothenburg on seven popular street tree species showed that transpiration is positively correlated with air cooling during sunset and shortly after [159]. The benefits associated with reducing the urban heat island by urban trees can significantly reduce the costs of cooling buildings. Increasing tree plantings has a comprehensive impact on improving urban residents' quality of life [160]. Interestingly, in a study of six species of urban trees in Dresden (*Aesculus* × *carnea* 'Hayne', *Corylus colurna*, *Ginkgo biloba*, *Liriodendron tulipifera*, *Tilia cordata* 'Greenspire', *Ulmus* × *hollandica* 'Lobel'), small-leaved linden trees showed the highest air-cooling efficiency [161]. However, it should be emphasized that cooling due to transpiration is dependent on access to water. Higher air temperatures and droughts increase the transpiration demand, causing a cooling effect on the leaf blade and its surroundings. However, water in the soil must be available for proper transpiration [154]. In addition, as shown by research conducted in Great Britain on five urban tree species (*Sorbus arnoldiana*, *Crataegus laevigata*, *Malus* 'Rudolph', *Prunus* 'Umineko' and *Pyrus calleryana*), the condition of trees is also an important aspect regarding the effectiveness of transpiration cooling. Urban stresses reduce the ability of trees to reduce temperatures in the environment [162].

Another important benefit of planting trees is the removal of air pollution. Numerous studies demonstrate that leaves are able to retain suspended dust and to absorb gaseous pollutants. This effect is multiplied in the case of trees that are characterized by an unusually large number of leaves in the crown, and therefore high values of total leaf area. Experiments carried out in China have shown that areas covered with trees have a lower $PM_{2.5}$ content in the air [163]. Research conducted in Warsaw and Stavanger in 2009–2010 revealed suspended dust PM_{10} and $PM_{2.5}$ on the leaf surface and in waxes [164]. Among the four tree species studied in Warsaw (*A. campestre*, *F. excelsior*, *P.* × *hispanica*, *T. cordata*), small-leaved lime trees accumulated the highest content of PM_{10} on the leaf surface and in waxes [165]. An interesting comparative study [158] gathered data on urban trees growing in 328 cities in 60 countries. Among 100 of the most popular species, the seven most effective in terms of $PM_{2.5}$ removal species were coniferous. However, in the first 20, there were common species such as *Acer rubrum*, *Populus alba*, *Salix alba*, and *Tilia tomentosa* [166]. The ability to accumulate suspended dust depends on the structure of the leaf blade, and the amount of accumulated dust increased with the course of the growing season [167]. A study conducted in Beijing revealed that leaves with dense hair accumulated more $PM_{2.5}$ than those with a smooth surface [168]. The authors also underlined the fact that coniferous species accumulate more particulate matter than broadleaved trees and are more effective at recapturing particles after rain events. Trees also contribute to the purification of air from gaseous pollutants. Research conducted in four parks in Rome showed that, in addition to large clusters of trees, alley trees and hedges have a significant impact on carbon dioxide absorption (CO_2 sequestration) [169]. In addition, trees contribute to the removal of PAHs [170], CO, NO_2, and SO_2 [114,171]. A two-year experiment carried out in Warsaw on small-leaved linden leaves showed the ability of this species to accumulate micro-dusts, PAHs, and heavy metals in their leaves. During the growing season, all foliage from one average tree accumulated 4.81 g of suspended dust (0.19 g $PM_{2.5}$), 4.38 g of PAH, and 1.27 g of heavy metals (including Pb, Cd, and Cu) [172]. Aside from absorbing and immobilizing both gases and solids, trees also contribute to improving air quality by producing oxygen as a byproduct of photosynthesis [173]. Trees indirectly contribute to reducing emissions from heating or air conditioning by reducing energy expenditure. Properly planted trees around buildings can reduce the spending on air conditioning in the summer and heating in the winter, thanks to shading, transpiration, and wind suppression [156]. Due to the ability of trees to cool the environment and to absorb gas particles, there is often a reduction in ozone pollution due to the presence of dendroflora [174]. The capacity of trees to affect ozone levels depends on the cooling efficiency as a result of transpiration, shading by the crowns of a given species, and the emission of volatile organic compounds. In a report on one of the districts of New York, species that most effectively removed ozone from the environment included *Betula* ssp., *Fraxinus* ssp., *Crataegus* ssp., *Ulmus* ssp., and *Tilia* ssp., among others [175].

Another major problem for city dwellers, which can be addressed by tree planting, is high noise levels. In Europe, around 80 million people are exposed to excessive noise. Hearing, sleeping, and even cardiovascular problems are just some of the effects of exposure to high noise levels among urban residents. Meanwhile, city parks are enclaves of peace and quiet; due to contact with nature and calm sounds, the physical and mental health of the users of these areas are improved [176]. Moreover, greenery has a positive effect on noise perception, not only as a mechanical barrier for sound but also due to audio–visual interactions [177].

4.5. Economic Benefits

Another benefit of trees in urban area is the management savings connected to ecological services. A large range of values assigned to specific tree functions in urban ecosystems can be found in the literature. Mullaney et al. [178] developed a range of these values based on their analysis of research works from all over the world (published from 1999 to 2011). The savings provided by one tree as a result of limiting the surface runoff of rainwater was estimated to be between USD 2.78 and USD 47.85 per year. The benefits of absorbing pollutants by trees are estimated to be between USD 1.52 and USD 34.50 per year. The estimated benefits of CO_2 removal are between USD 0.33 and USD 4.93. Energy savings due to wind protection in the winter and the shading of buildings in summer are estimated to be between USD 2.16 and USD 64.00. The annual overall benefit per tree is between USD 21 and USD 159, including care expenses [179]. The estimated annual benefits of urban parks in Toronto, Canada in 2008 was USD 26,326 with USD 16,665 of environmental and USD 9661 of aesthetic value. The delivered benefit-to-cost ratio was estimated as 3.4:1 [179]. As Akbari et al. [180] estimated, the total value of the benefits of planting trees based on the example of the United States was valued at USD 10 billion a year. Based on the example of Lisbon, it was estimated that for every dollar invested in urban trees, residents gained a saving of USD 4.84 [181]. Over 90% of city residents pay attention to the presence of greenery in an area when buying real estate. The willingness to support planting projects depends on income, sex, education, and other factors [182]. Important tools for estimating the benefits of trees are computer programs such as i-Tree. Those programs help to improve tree management and analyze the costs and benefits of urban trees [183].

5. Improper Management and Possible Disadvantages of Urban Trees (Disservices)

In addition to the numerous benefits of urban trees, there are also disadvantages. Some of them, like falling leaves or pollen allergenicity, are connected to trees' phenological phases and are an inseparable part of tree vegetation. However, most issues are connected to improper management and can be avoided. One common issue is the shading of flats by trees planted too close to buildings and the littering of sidewalks and lawns with falling leaves in autumn. Another issue is the influence of pollen, fruit, nectar, or honeydew falling on cars standing under tree canopies. The wide branches of trees near buildings can provide access to upper floor windows and may facilitate burglaries and thefts. The threat of the branches of large trees breaking during strong winds or gales is often the basis for applying to have them cut down [184]. This aforementioned problem can also damage urban infrastructure such as pavements [185], sewage pipes [186], or buildings due to tree roots [187].

Most of the conflicts between human-engineered and biophysical systems, called "green and grey" infrastructure [188], are due to constructional or design errors, as well as the improper selection of a species. Root damage is a major cost for cities and citizens and is often recognized as the negative side of planting large trees [179]. In Great Britain, 30-year-old *Prunus serrulata* 'Kanzan' trees that were planted in pits (0.7 × 0.7 m) damaged the walls of nearby buildings and the sidewalk within 7 m of the tree trunks [189]. Research conducted in Milwaukee over 26 years showed that planting trees on a wide lawn (optimally, 2-3 m from the sidewalk border), away from construction objects, increased the survival of trees, while minimizing the risk of collision with infrastructure [190]. Aside from absorbing detrimental particles, trees can also emit harmful compounds. Depending on the species, trees emit a different amount of volatile organic compounds, such as terpenes, which contribute to ozone pollution and the formation of secondary particles [191,192]. Trees can also indirectly increase pollution by blocking the wind and preventing ventilation [193]. Another problem is also the toxicity of some species and pollen allergenicity. Particular caution is recommended, especially in schools and kindergartens, when planting species such as *Thuja* sp., *Juniperus* sp., or *Taxus baccata*, as well as *Cotoneaster horizontalis*, *Robinia pseudoaccacia* or *Symphoricarpos albus*, due to the harmfulness of different parts of plants. Due to pollen allergenicity, it is recommended to limit the planting of species such as *Betula pendula*, *Robinia pseudoaccacia*, *Quercus robur*, *Corylus colurna*, *Aesculus hippocastanum*, *Platanus acerifolia*, as well as species of the genus *Tilia*. [194]. Proper tree selection, management and care treatments are equally important. Ensuring a high level of these three areas is essential in obtaining the optimal benefits of tree planting.

6. Future Perspectives

Our knowledge of the interactions of trees and their environment in relation to the subsequent impacts on ecosystem services and disservices is constantly expanding and evolving. In a changing climate, the survival of urban trees is at risk. As we presented, new stress factors are appearing with global development. The anticipated increase in the size of cities, greater urbanization, and population density contribute to the risk of severe drought and flooding events, heat waves and other environmental issues. As we have presented, a city structure generates a combination of factors that are stressful for tree growth and development. These factors often occur at the same time, resulting in interactions and negative synergies. There is a need for multidirectional studies that take into account several factors at once. Laboratory experiments in which one or two stress factors are used under controlled conditions often have limited value in reference to real environmental conditions. We also recommend finding new methods of such studies for vivid presentation to the average city inhabitant. Community awareness and involvement is crucial for trees' survival. As green spaces in cities are reduced, the maintenance of buildings and infrastructure will become more expensive. To ensure the optimal benefits of urban trees, greater emphasis should also be placed on the selection of species. However, the authors want to underline the complexity and difficulty of "proper" planning in view of the modern vastness of information. Despite modern and extensive knowledge, proper species selection is extremely difficult. While one specimen is urban stress resistant and has bioaccumulation properties, it can be allergenic or emit volatile compounds. In such circumstances, the selection of species remains an extremely complicated issue, with a constant balancing of the pros and cons. Moreover, the proper propagation and acclimation of plants for urban areas is a subject for development in the coming years. The use of adapted species for urban conditions will not only ensure maximum environmental benefits, but will also reduce the costs associated with replacing trees. Furthermore, the inadequate quality of nursery material is still a scarcely noticed issue in this field. There is a need for long-term monitoring, which allows the development of good practices based on reliable data in a given environment. The prospects for improving trees' growth conditions, while maintaining the living comfort of inhabitants and balancing the costs, should be the main objectives in this field in the coming years.

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