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Review

Trees in Sponge Cities—A Systematic Review of Trees as a Component of Blue-Green Infrastructure, Vegetation Engineering Principles, and Stormwater Management

Michael Richter *, Kirya Heinemann, Nadine Meiser and Wolfgang Dickhaut

Department of Environmentally Sound Urban and Infrastructure Planning, HafenCity University Hamburg, 20457 Hamburg, Germany
* Correspondence: michael.richter@hcu-hamburg.de

Abstract: Combining street trees with stormwater management measures can, in some circumstances, both increase tree vitality and reduce the risk of flooding by directing stormwater into tree pits. Using systematic review methods, this study aimed to provide an overview of the vegetation engineering systems being researched and applied that combine tree planting with urban stormwater management. We also sought to identify the positive as well as possible negative impacts on urban hydrology and tree health. It has been shown that diverting rainwater from impervious surfaces into tree pits has considerable potential for stormwater management and for improving tree health by reducing drought stress in urban trees. Worldwide approaches to optimizing tree pits for rainwater infiltration and water supply are promising. Different systems and substrate types have been tested, and street trees generally show good vitality, although systematic long-term monitoring of tree vitality has rarely been undertaken. There is still a need for research into temporary water storage for dry periods.

Keywords: urban trees; sponge city; water-sensitive urban design; blue-green infrastructure; passive irrigation systems

Citation: Richter, M.; Heinemann, K.; Meiser, N.; Dickhaut, W. Trees in Sponge Cities—A Systematic Review of Trees as a Component of Blue-Green Infrastructure, Vegetation Engineering Principles, and Stormwater Management. *Water* **2024**, *16*, 655. https://doi.org/10.3390/w16050655

Academic Editor: Enedir Ghisi

Received: 30 December 2023
Revised: 8 February 2024
Accepted: 20 February 2024
Published: 23 February 2024

1. Introduction

Urban areas are challenged by extensive impervious surfaces, damaged soils, little room for greenspace or for stormwater management facilities, and the increasing risks of climate change impacts like extreme weather events and the urban heat island effect (UHI). Blue-green infrastructure (BGI) like green roofs and walls, swales, infiltration trenches, and trees have significant potential to help urban areas adapt to climate change by capturing, storing, evaporating and transpiring stormwater runoff that would otherwise enter sewer systems [1,2]. BGI provides additional ecosystem benefits, including biodiversity enhancement, air quality improvement and mitigation of UHI effects [3–6]. With the expansion and densification of cities and the ongoing impacts of climate change, increasing amounts of stormwater must be handled, and existing sewer systems are often already overwhelmed. Urban green infrastructure can decrease the pressure on existing drainage systems by absorbing stormwater from paved surfaces, delaying discharge and increasing groundwater recharge and evapotranspiration (ET) by plants. Additionally, the recycling of stormwater could improve the vitality of urban vegetation, which often suffers from drought. Managing stormwater locally with tree pits could have additional benefits like helping to improve the living environment of the trees and decreasing root intrusion into underground pipes [7]. Healthy street trees provide a number of benefits for the urban environment and increase the livability of cities by reducing stormwater runoff, improving air quality, storing carbon, providing shade, ameliorating UHI effects and enhancing biodiversity [8]. They can also add beauty and character to the urban landscape, increase the value of residential and commercial areas, reduce annual building energy consumption by moderating the local climate, filter harmful pollutants from the air, reduce unwanted noise and help slow down cars [9]. The challenging environment they are exposed to can significantly reduce the services street trees provide. Urban trees often have a very limited amount of space to grow, and rainwater is drained away from paved surfaces to stormwater drains and not down into the soil [7]. Trunk and crown damage is also a problem for many of the trees standing close to roads [7]. Urban soils and soils in tree pits are often compacted by car, bicycle and pedestrian traffic, construction works and parking. Soil compaction impacts plant growth and limits useable rooting space by crushing the macropores, which restricts water drainage and subsequent aeration and poses a physical barrier to root penetration [10]. Compacted soils can prevent water from reaching a tree's roots or from properly draining—the consequences of which can be fatal for a tree [11]. It has been shown that even small increases in soil density negatively influence root growth [12] and that trees planted in uncompacted soil beneath pavement grow faster, are healthier in visual appearance and create more canopy shade than trees growing in compacted urban soils [13]. Lack of rainwater infiltration can lead to high levels of drought stress [14,15]. Sufficient space, appropriate soil, sufficient gas exchange, adequate drainage and a supply of water are vital for growing trees in urban landscapes [9]. Additionally, climate change may lead to increased mortality of street trees due to an increase in extreme events [15]. When considering trees as blue-green infrastructure, it is important to note that they receive rainwater from a specific catchment area (e.g., streets, parking lots and roofs) and not just the rain that falls in the area of the tree canopy. This represents an urban or small-scale nature-based solution (NbS), also known as a passive irrigation system, combining blue and green (and sometimes grey) elements to provide multiple benefits [16,17]. Combining street trees with stormwater management measures can, in some circumstances, both increase tree vitality and reduce flooding risk by directing stormwater into tree pits [18]. The use of trees within other blue-green infrastructure types, like bioswales, green roofs and tree box filters, could further improve their performance in terms of stormwater management [19]. Trees reduce stormwater runoff and soil erosion through direct retention on leaves and branches when they become wet (interception), runoff of water via the trunk (stem runoff) and infiltration through the soil [20]. Additionally, substrates filter pollutants from stormwater before it infiltrates into groundwater [11]. Adapting planting sites to meet the needs of urban trees can be achieved primarily through the design of the planting pit/BGI and/or the composition and layering of planting substrates. In terms of technical feasibility, there are several options for combining water sensitive urban design (WSUD) and tree pits. The recycling and re-use of rainwater for the irrigation of urban trees could be a win–win situation for water storage, heavy rainfall prevention and groundwater recharge while contributing to a better water supply for trees. Technical systems and the possible benefits and challenges of combining WSUD and tree sites, i.e., the integration of trees in blue-green infrastructure, is covered in this article. The following research question served as the basis for this study and for conducting the systematic review:

- Which vegetation–technical solutions are available for urban tree sites as blue-green infrastructure, and what are the possible advantages and disadvantages for rainwater management and tree health?

The aim of this study is to provide a comprehensive overview of the vegetation engineering systems being researched and applied that combine tree sites with urban stormwater management. In addition, an attempt was made to identify the positive and possible negative effects on urban hydrology and tree health.

2. Materials and Methods

A systematic review was carried out to answer the research question. Systematic reviews provide an overview of a clearly formulated scientific question that systematically identifies, selects and critically assesses relevant research results using specific methods [21]. In the context of this work, a systematic review was conducted according to the guidelines of the Collaboration for Environmental Evidence [22]. These guidelines are freely available and therefore comprehensible and reproducible and are similar to other guidelines for systematic review procedures [23]. The method originally comes from and was mainly used in the health or medical sciences. However, it is now also regularly used in the environmental and natural sciences [24]. This specific, robust and transparent method was chosen in order to obtain a broad and transparent overview of the findings published in scientific studies in English and indexed in databases. However, it is not possible with this method to cover all the scientific literature ever published on the subject. There are a number of issues that need to be considered when using the method and evaluating the results. Due to the limitation to English language articles, a certain amount of research not published in English will not be included. Keywords must be chosen very carefully and should also be tested, as the use of inappropriate keywords may result in some relevant articles not being found, as the technical terms of systems in geographical regions differ. The definition of specific characteristics and conditions that leads to studies being included in an analysis or not depends on the judgement of the respective researchers and is therefore a source of variation in the final results. In this paper, the conditions were formulated on the basis of thematic relevance to the research question and the quantitative analysis of BGI tree systems. The limitation of the literature search to a certain number of databases also means that some studies not published in the journals listed in the databases were not included in the analysis. To answer our research question, we used the keyword combination ("urban tree*" OR "city tree*") AND (stormwater OR runoff OR rain* OR precipitation OR cloudburst). These keywords were then used to search for studies in scientific databases. The databases searched were Web of Science Core Collection (www.webofknowledge.com) and Scopus (www.scopus.com). The articles were searched in the databases according to the occurrence of the given keyword combinations within the information, i.e., whether the keywords occur in the title, article keywords or summary of the articles. In the next step, the studies were selected from the database search over several stages with regard to thematic relevance and the possibility of extracting qualitative and/or quantitative statements. In the first step (screening), all titles found in the databases were checked, and obviously unsuitable articles were cast aside. After that, all abstracts were read to check suitability. Unsuitable studies were again eliminated. After removing duplicates, all remaining studies were classified as possibly relevant for extraction of qualitative and quantitative data and analyzed on the basis of their full text. In the end, 39 studies were included in the analysis. A list of these studies can be found in List S1 in the Supplementary Materials. The procedure for selecting the scientific studies is illustrated in Figure 1.

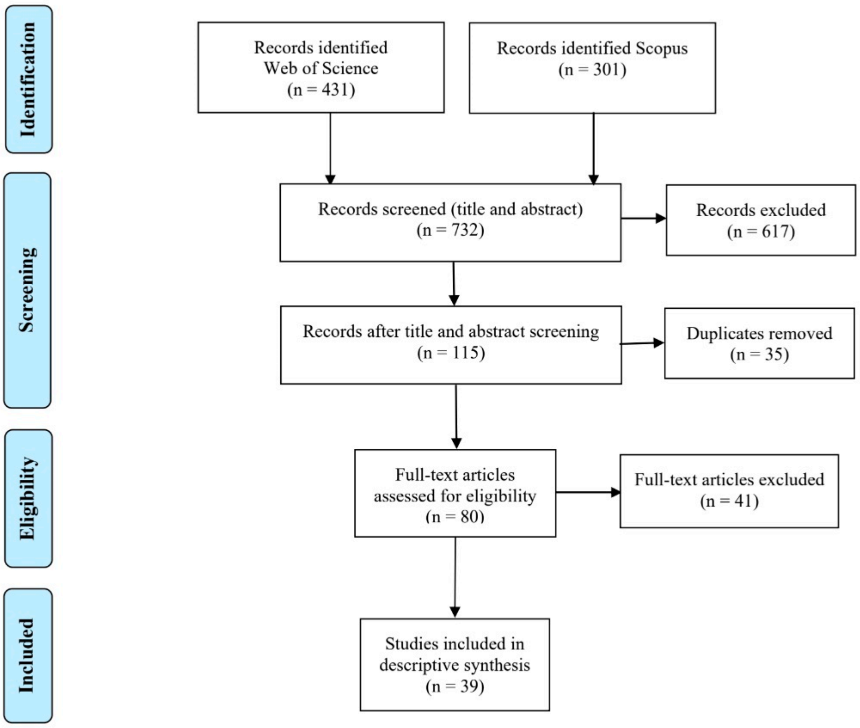

Figure 1. PRISMA flow diagram [21] illustrating the approach of selecting scientific studies that investigated blue-green infrastructure combined with trees in urban areas via a systematic review.

3. Results

3.1. Publication Years, Study Locations and Observation Periods

Publications included in the descriptive analysis were published between 2008 and 2023. There seems to be growing interest in the topic in the scientific literature, which can be seen in the number of publications per year from 2017 onwards, as shown in Figure 2. This is also the case in other systematic reviews about NbS or BGI, e.g., [17,25]. This could be an indication of the increasing global importance of climate change impact adaptation measures.

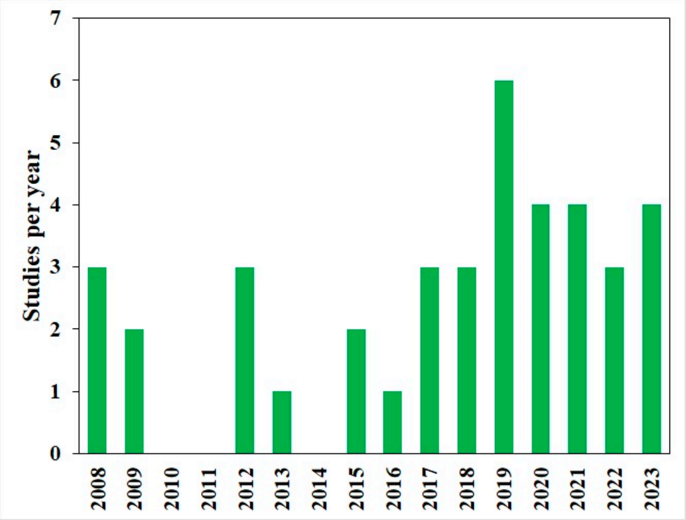

Figure 2. Analysis of the number of reviewed publications per year.

The geographical focus of the studies is apparent (Figure 3). By far, most studies were conducted in the United States (16) and Australia (10). Other countries are only represented by one study each in this review. This indicates a much longer tradition of BGI systems combined with trees in the USA and Australia. This may be due to the fact that in some countries, the tradition of scientific publication in the field of vegetation engineering is not as strong as in the USA and Australia. In addition, in some countries, these systems have only been the focus of scientific attention for a few years, and therefore few studies have been published in English. The authors can report this to be the case for some European countries, such as Germany. In general, while studies on BGI tree systems can be found in Asia, Europe and North America, regions and cities in the southern hemisphere have hardly been investigated in this respect (or the studies have not been published in the international peer-reviewed literature).

The observation periods of the different studies were also analyzed (Figure 4). If indicated in the text, we extracted the duration measurements from each study (n = 27) as well as the time period between the planting of the trees and the end of measurements (n = 21). As an example, Ref. [26] measured the weekly water quality performance of bioretention mesocosms from June to October 2017 (observation period = 5 months). Trees in these mesocosms were planted in fall of 2016, so the period of tree planting to the end of observation is set to 12 months. The box-plots in Figure 4 indicate that the observation periods are in most (but not all) cases shorter (mean value: 17 months; median: 7 months) than the time from planting till the end of the measurements (mean: 27 months; median: 18 months). The range (min–max) of the observation periods is in the same magnitude (1–123 months) as the time from tree planting till the end of measurements (4–132 months).

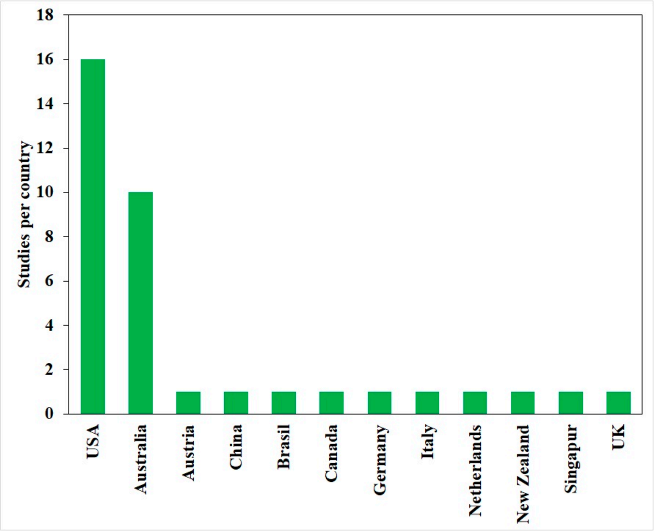

Figure 3. Analysis of the number of reviewed publications originating from different countries.

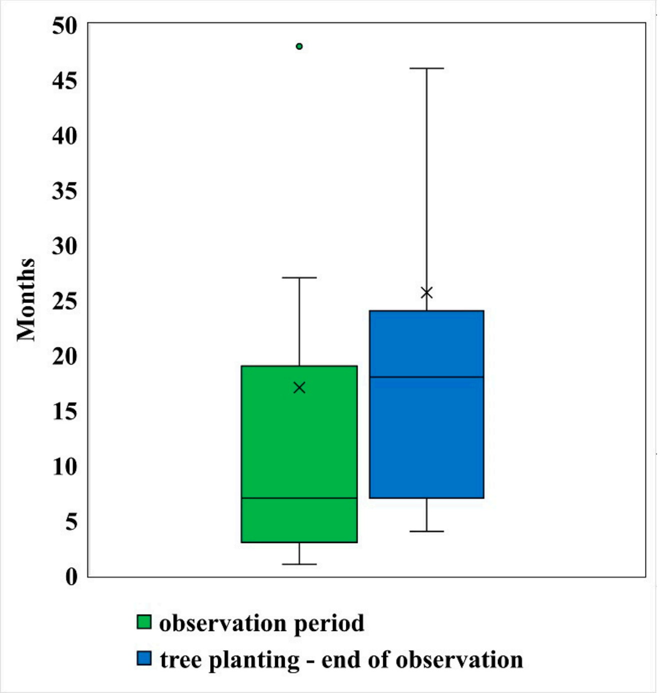

Figure 4. Box-plots of observation period length (green, n = 27) and the time period from when the tree was planted until the end of the measurements (blue, n = 21) for the analyzed studies. The horizontal lines in the boxes are medians, and crosses are mean values.

3.2. BGI Tree Systems

In the reviewed studies, different systems were used and tested to analyze the effects of redirecting stormwater runoff from roads, parking lots, etc., to passively irrigate street trees, i.e., passive irrigation systems. The common goal of the studies seemed to be to reduce stormwater runoff volumes and reduce tree drought stress and increase growth. The studied tree BGI has the function of natural green space with improved rainwater management, often for an area larger than the vegetation surface itself [27]. From the studies, six different types of BGI systems were typologized:

- Cell/suspended pavement systems;
- Structural soils;
- Tree trenches;

- Tree box filters/raingardens/biofilters;
- Rainwater harvesting systems/cisterns;
- Infiltration trenches;
- Permeable pavements.

This differentiation is a suggestion and is based on the reviewed studies. The typology is not exhaustive, and individual types are often merged or combined with one another. In the investigations, many tree species were tested for their suitability as part of a BGI system. The most generically suitable trees, as noted in [28], in permeable pavements were *Acer platanoides*, *Acer pseudoplatanus*, *Alnus glutinosa*, *Betula pendula*, *Cupressus* × *leylandii*, *Robinia pseudoacacia*, *Platanus* × *acerifolia*, *Quercus palustris* and *Tilia* × *europaea*. In contrast, the most generically unsuitable trees for streets and permeable pavements were *Aesculus hippocastanum*, *Populus* spp., *Salix babylonica*, *Tilia platyphyllos* and *Ulmus procera* [28]. Further tested tree species in BGI were *Acer rubrum*, *Agonis flexuosa*, *Betula nigra*, *Callistemon salignus*, *Callistemon viminalis*, *Calophyllum inophyllum*, *Cedrus deodara*, *Celtis australis*, *Cinnamomum bodinieri*, *Elaeocarpus decipiens*, *Eucalyptus polyanthemos*, *Fraxinus pennsylvanica*, *Fraxinus ornus*, *Gleditsia triacanthos*, *Gymnocladus dioicus*, *Koelreuteria paniculate*, *Lagerstroemia indica*, *Ligustrum lucidum*, *Liquidamber straciflua*, *Lomandra longifolia*, *Lophostemon confertus*, *Magnolia grandiflora*, *Melaleuca quinquenervia*, *Metasequoia glyptostroboides*, *Osmanthus fragrans*, *Pinus taeda*, *Platanus occidentalis*, *Platanus orientalis*, *Prunus cerasifera*, *Prunus serrulata*, *Pyrus calleryana*, *Quercus bicolor*, *Taxodium distichum*, *Tristaniopsis laurina*, *Ulmus Americana*, *Ulmus davidiand*, *Ulmus parvifolia* and *Zelkova serrata*.

Soils or substrates are the basis for all the analyzed systems. They store rainwater during and after a storm, making it available for tree growth and accessible between saturation and the wilting point [29]. The key to the healthy growth of large trees is a large volume of uncompacted soil with adequate drainage, aeration and fertility [30]. The minimum soil volumes for tree plantings for several cities is about 0.06 m^3 (2 cubic feet) of uncompacted soil volume per 0.1 m^2 (1 square foot) crown volume [29]. Some sample city requirements are as follows [29]:

- An amount of 17 m^3 for small, 25.49 m^3 for medium and 34 m^3 for large tree species (Emeryville, CA, USA);
- An amount of 31.15 m^3 for individual tree pits and 15.57 m^3 per tree for multiple tree pits (Toronto, ON, Canada);
- An amount of 21.24 m^3 per tree (Denver, CO, USA);
- An amount of 28.32 m^3 per tree (Charlotte, NC, USA).

Basically, the properties of the substrate need to be such that, on the one hand, as much water as possible is stored for a long time to supply the trees with water. On the other hand, the substrate must be permeable enough to prevent waterlogging and to allow water to infiltrate quickly during heavy rainfall. In the following, we answer the research question about the available vegetation engineering solutions for urban tree sites as blue-green infrastructure (Sections 3.2.1–3.2.7) and explain the potentialof these systems in terms of stormwater management (Section 3.3) and tree health (Section 3.4) and potential challenges (Section 3.5). Different principles and technical approaches that have been implemented in different regions and that have independently been found to be useful in the studies reviewed are briefly presented. Technical details of the systems are not presented; only basic functions are explained. For the details of each principle, please refer to the sources listed in the sub-chapters.

3.2.1. Cell/Suspended Pavement Systems

Suspended pavement systems are geocellular structures made of concrete or plastic and are designed to transmit the load from vehicles, pavement and pedestrians to a compacted sub-base serving to protect the soil (and rooting volume) inside the cells from compaction [29,31]. The cells can be filled with tree substrates or specific biofiltration material designed for bioretention, to detain, store and treat urban stormwater runoff [31]. These systems can be used to extend rooting volume, e.g., under streets, and create extensive rooting volumes to grow large and mature trees in urban areas [29]. Figure 5a shows a simplified schematic sketch of a suspended pavement system. The systems can be equipped with underground drainage pipes to convey the portion of runoff that does not exfiltrate into underlying soils. In practice, suspended pavement systems are also used without an external supply of rainwater. If they are supplied with external rainwater, then it is either superficially (e.g., through curb inlets) or through street drains or underground pipes.

3.2.2. Structural Soils

Structural soils basically have the same function as suspended pavement systems. They should protect the rooting zone from compaction. Structural soils consist of crushed stones mixed with fine-grained mineral soils and have a high load-bearing capacity that permits tree root growth [32]. Structural soils are compacted to meet engineering standards, typically designed to support streets or car parks [33]. The soil mixture within the voids (typically 20–35 vol%, depending on the grain size of the coarse stones) between the stones functions to provide roots with space and nutrients for growth [34]. The fine soil components in the interstitial spaces can be sandy or loamy-clay substrates with mixtures of organic materials (e.g., humus, biochar). Structural soils have high porosities of approximately 30–35% [32]. Three main types, subdivided according to the size of the coarse soil fraction, have emerged: 'sand-based substrates' or 'compacted sand structural soils', 'medium-size aggregates' (coarse soil fraction with grain sizes of 25–100 mm) and 'large-stone skeleton substrates' (coarse soil fraction with grain sizes of >100 mm). Structural soils should not be used as a substitute for substrates in planting pits but as the structural section under pavement that surrounds tree planting areas, where roots would normally not be able to penetrate due to compaction [32]. Like suspended pavement systems, structural soils can also be used without an external supply of rainwater. If they are supplied with external rainwater, this is done on the surface via street drains or with underground pipes. Figure 5b shows a simplified schematic sketch of a tree pit extending under pavement with structural soil.

3.2.3. Rainwater Harvesting Systems/Cisterns

Tree pits can be combined with rainwater harvesting systems or cisterns to automize irrigation (moisture-sensor controlled) or based on soil water tension, e.g., via pearl hoses [35] or fiberglass wicks [36]. With systems like these, it is possible to irrigate the root zone when local soil conditions in the tree rhizosphere dictate a need via a water potential differential [36]. These rainwater harvesting systems can contribute to flood prevention by capturing, retaining and detaining stormwater and can help increase the drought resistance of urban tree pits [36]. When their storage tanks are empty, they can be manually refilled [36]. They can be built as low-technology, self-managed systems requiring low maintenance effort. Figure 5c shows a simplified schematic sketch of a tree pit combined with a rainwater harvesting system.

3.2.4. Permeable Pavements

Permeable pavements are a way of making sealed surfaces permeable to rainwater and thus enabling it to infiltrate over large areas, below roads and sidewalks, for example. Permeable pavement is increasingly being used as a solution for paving roads, car parks and greenways, under the design concept of building a sponge city [37]. However, there are still a number of challenges to widespread implementation in practice. These include interlayer shear performance under traffic loads [37] and permeability loss due to clogging (see Section 3.5.2), which leads to more frequent maintenance and increased costs [38]. When integrated at the base of urban trees, permeable pavements can help to control stormwater runoff by facilitating infiltration and stormwater retention [39]. The drought stress of urban trees may be reduced by allowing water to infiltrate into the subsoil [14]. Permeable pavements have the potential of improving growing conditions for roots and reducing water shortage and nutrient uptake issues for trees [14]. Figure 5d shows a simplified schematic sketch of a tree pit covered with permeable pavement.

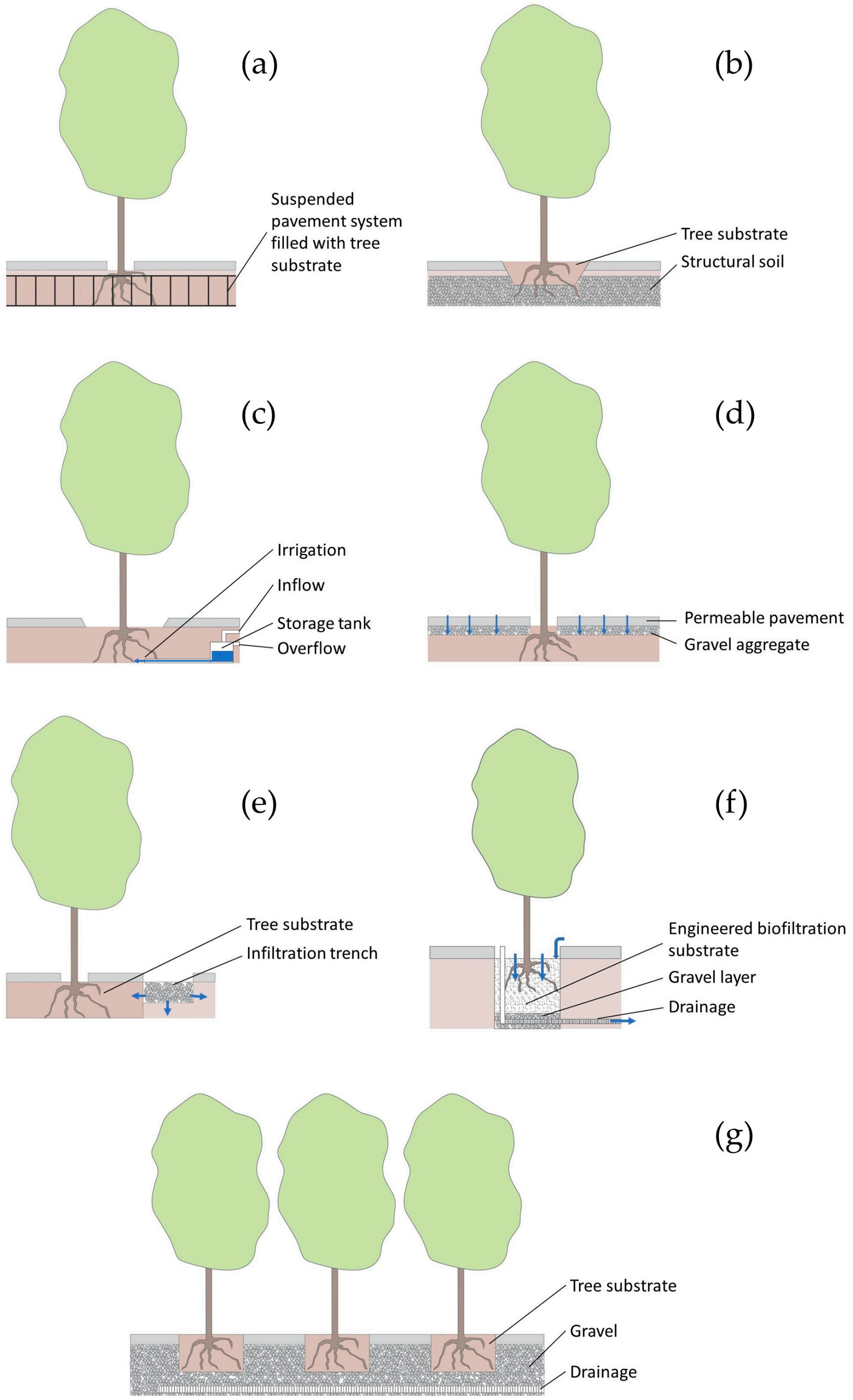

Figure 5. Sketch of principles and basic technical details of BGI tree systems: suspended pavement systems (**a**), structural soil systems (**b**), rainwater harvesting systems (**c**), permeable pavement systems (**d**), infiltration trenches (**e**), biofiltration systems (**f**) and tree trenches (**g**).

3.2.5. Infiltration Trenches

By placing infiltration trenches near street trees, they can receive stormwater from sealed surfaces larger than the area of the tree canopy. Infiltration trenches can be placed, e.g., in green strips with a curb inlet to receive stormwater from streets [40,41]. As an example, ref. [41] placed the infiltration trench 1.5 m from the base of the study tree. This could be a possible solution to increase the transpiration rate of established trees and therefore increase their co-benefit for stormwater management [40]. Figure 5e shows a simplified schematic sketch of an infiltration trench installed near an established street tree pit.

3.2.6. Tree Box Filters/Raingarden Tree Pits/Biofilters

Bioretention systems are also known as biofilters, tree box filters, rain gardens or raingarden tree pits. Their design is often similar in that they typically consist of an engineered sandy soil media topped with mulch and various plants [42]. Stormwater runoff discharged into BGI from parking lots, roadways or other impervious areas slowly infiltrates through the sandy media, where pollutants are filtered out, adsorbed to soil particles or taken up by plants or microbes [26]. They are often connected to the sewer system via underground drainage pipes under the tree pits to drain off the purified water. Figure 5f shows a simplified schematic sketch of a biofiltration tree pit.

3.2.7. Tree Trenches

A typical row of street trees, i.e., tree trenches, are connected below ground by an elongated, gravel-filled trench [43]. The pits of single trees are embedded in the gravel. Stormwater runoff from adjacent roadways and other impervious surfaces enters at one end of the trench and is distributed through the trench via a perforated pipe; this design is intended to allow stormwater to reach the tree pits during large storms, irrigating them from below [43]. Tree trenches could enhance stormwater interception, infiltration and removal [44]. A simplified sketch of a typical tree trench is shown in Figure 5g.

The different BGI systems or system components are applied more or less globally in a similar way. The technical details differ, but the basic principles and modes of operation are comparable in the studies. In most cases, the systems are used to provide the following services:

- Reduce the compaction of tree substrates by traffic (and therefore enable rooting);
- Expand the root zone under traffic areas;
- Reduce, delay and retain stormwater runoff;
- Supply trees with more water than usual (increase the catchment area beyond the area of the crown);
- Filter rainwater.

The systems are often combined with each other in order to achieve as many of the individual objectives as possible.

3.3. Hydrologic Performance

The hydrologic performance results of the reviewed studies that refer to the tree pit systems as a stormwater control measure are presented.

3.3.1. Infiltration

Trees that are part of stormwater control measures seem to have the effect of increasing infiltration rates [32,44–47]. Trees can increase the soil's ability to infiltrate, store and percolate stormwater runoff by root penetration into surrounding soils [44], even under impervious zones [46]. Trees have more developed roots than herbaceous plants, resulting in better protection and improvement with respect to the soil's physical and chemical properties [45]. Therefore, the tree root system has a significant advantage over herbaceous plants in increasing the infiltration capacity under impervious zones and within soil below 15 cm [45]. Soil infiltration below 15 cm can be improved by tree roots by altering the porosity and bulk density [45]. Additionally, tree roots can alter the drainage properties of compacted subsoils under certain conditions [32]. According to their root characteristics, trees have deep, medium or shallow root distributions, which can be used as a basis for selecting plants to improve soil infiltration [45]. The order of overall benefits for improving soil infiltration is trees with deep > medium > shallow root distributions [44,45]. This means that the deeper the root distribution, the greater the influence the root system has on soil infiltration [44]. However, due to the variable soil conditions and challenges that trees are exposed to in urban environments, tree species with characteristically deep roots may not necessarily be able to deeply root themselves when grown in the urban environment [32,45,48]. Planting trees can nevertheless be used as an effective way to improve soil infiltration [45] and can help store more runoff and reduce volume for receiving waters and sewer systems [44]. Irrespective of the change in infiltration capacity due to roots, the substrates or structural soils used in BGI tree systems often have a very high infiltration capacity due to their coarse-grained structure [34,46].

3.3.2. Retention

The amount of stormwater retention for BGI tree systems is affected by a variety of factors, including the catchment size, rain event properties (intensity, duration, amount), the maximum water capacity of the substrate, available storage (tree pit volume/cistern), exfiltration rate (drainage/exfiltration in the surrounding soil), ET rate of the trees and possible emergency overflows. There are major differences in the retention capacity of individual systems. Ref. [49] reports that system size and design can have a great influence on runoff reduction performance and thus explain the relatively low retention rates of, e.g., 5% of annual runoff from small tree pits (0.7 m^2, <1% proportion of catchment area) compared with 24% for medium-sized systems (6 m^2, 2.4–4.6% proportion of catchment area) in Melbourne [18,40]. Higher retention levels were reported, e.g., by [31], with 79% and 83% capture of stormwater by suspended pavement systems with 12.5% and 20% proportions of the catchment. Ref. [18] showed that it is possible to achieve a 90% reduction in annual runoff, even in dense urban areas with low conductivity soils, when tree pits have a size between 2.5% and 8% of the impervious catchment area. Combining rainwater harvesting systems with tree pits could improve retention performance by offering quickly available rainwater storage (when empty) and therefore could increase the catchment area without significantly impacting performance. For example, Ref. [35] showed 90–92% annual rainwater retention at a tree-pit-to-catchment-area proportion of only 2%. To increase the size of the tree pits and therefore the available storage volume, it is recommended to establish hydrologic connectivity between individual tree pits, e.g., via trenches [43], suspended pavements or structural soils. Runoff retention performance of BGI tree systems can be further improved by selecting trees with high ET rates [18], which rapidly transpire the intercepted stormwater, increasing the storage capacity before the next runoff event [18]. Even more potential could exist through the temporary storage via interception or foliar retention on leaves and also via tree branches and stems [44]. The amount of storage is typically the first 2–4 mm of rainfall, e.g., as specified in [50], depending on the amount of leaf area, rainfall intensity and duration, climatic conditions and tree crown structure [44]. Open-crowned trees in urban areas have been found to have differing interception coefficients when compared to rural forest trees, due to greater branch and stem bark area and greater crown volume or live crown ratio, as a result of the lack of direct competition for sunlight [44].

3.3.3. Evapotranspiration

Increasing the ET of BGI trees can increase the performance of such systems by increasing their capacity to intercept runoff, reduce the volume of runoff [22] and increase evaporative cooling. From a stormwater engineering point of view, it may be helpful to maximize transpiration losses in BGI tree systems when volume reduction is a key run-off management objective [51]. Hence, selecting trees with high transpiration rates could improve hydrologic performance [18]. Tree species with a large mature size and greater total leaf area will likely contribute more towards the hydrologic functioning of the system [52]. Crop factors can be used to estimate the volume of runoff transpired by plants in BGI systems and may be a useful metric for selecting tree species with high transpiration to improve the runoff reduction benefits [49]. They are typically determined under well-watered conditions to represent maximum transpiration rates and are commonly used to quantify transpiration relative to the reference ET of well-watered grass [18,49]. Transpiration rate losses are greater in BGI tree systems with higher water availability [51]. Therefore, it can be hypothesized that redirecting stormwater to trees could increase transpiration when there is limited access to water and the trees are often drought stressed [41]. However, redirecting stormwater did not increase transpiration in a study where trees already had access to enough water in the streetscape [41].

3.4. Tree Health

Besides hydrologic performance, the effect of combining trees with stormwater management measures on the development of healthy trees is of key importance, not only for improving the performance of BGI systems as a flood prevention tool but also for people's health and urban biodiversity. The results of the reviewed studies that refer to the effects of the tree pit systems on tree health are presented.

3.4.1. Root Growth

In principle, the passive irrigation systems should create more space for roots and ensure a better water supply. In the reviewed studies, the most studied effect on root development was the distinction between root growth under permeable vs. impermeable pavement. Roots under permeable pavement were more numerous than those under impermeable pavement [53,54]. A negative effect could be the observed shallower root system [55]. The shallower root development could increase undesirable interactions between roots and infrastructure and could also possibly decrease tree resistance to strong winds [55].

3.4.2. Stem Diameter Growth

The most widely used indicator of tree growth in the reviewed studies was stem diameter at 1.30 m height. The research hypothesis in most of the studies was that an additional supply of rainwater would increase tree growth. In most cases, this hypothesis was fulfilled. Ref. [30] compared different structural soils and suspended pavement and found that after seven years, trees grew best with suspended pavement. Stormwater discharge may improve the growth of street trees by 3- to 6-fold as compared to traditional street tree planting options, as reported by [34]. Permeable pavements seem to increase trunk diameter growth in various studies [14,54]. However, increased growth rates for trees in BGI systems was not reported in all of the studies. No significant treatment effect on stem diameter relative growth rates between trees receiving stormwater (infiltration trench) and control trees was found in [41].

3.4.3. Other Tree Health-Related Factors

Tree health in terms of plant performance was quantified using various other parameters. Refs. [36,56] determined higher biomass production due to a better water supply by BGI systems. Ref. [34] indicated significantly higher leaf areas (2-fold increase) of BGI trees compared to control trees. A negative influence on tree health in bioretention tree pits was reported by [42], where trees from five of the six species examined (*Acer rubrum*, *Betula nigra*, *Quercus palustris*, *Cercis canadensi*, and *Ulmus parvifolia*) were less healthy (smaller composite crown volume and composite crown surface area) than similar non-bioretention trees; only *Taxodium distichum* exhibited better health in bioretention.

3.5. Challenges

Several environmental and planning-related factors that contribute to tree health and hydrologic function should be considered.

3.5.1. De-Icing Salt

De-icing salt contamination in BGI tree systems can affect tree health through run-off of contaminated rainwater and/or salt spray. De-icing salt can significantly affect tree performance [56–58]. Salt spray can cause chlorosis and necrosis of leaves and buds [59,60], and salt accumulation in tree substrates/soils can increase osmotic stress for BGI tree roots and cause chlorosis [57,61]. This effect can be enhanced by long-term accumulation [58]. Accumulation can also displace soil nutrients [62,63], exacerbating the negative effect on tree health [56]. Studies have reported different ways of dealing with contamination. The degree of salt accumulation can be influenced by the physical characteristics of the substrates, such as soil compaction and texture [64]. In addition, the frequency and intensity of de-icing salt application in cities may change due to increased climate change [56]. This could mean that some regions will experience higher temperatures and therefore require less frequent use of de-icing salt. However, this varies greatly from region to region and is subject to very large uncertainties and climatic variations, so it is difficult to rule out the use of de-icing salt. According to [56], the selection of tree species with higher salinity tolerance is important for better tree growth performance, and the selection of tree species with low to moderate tolerance may increase osmotic and ionic stress, dehydrating plant tissues, impairing photosynthesis and accelerating leaf senescence. A safe way to maintain tree health seems to be to ensure that de-icing salt does not reach tree sites in the first place. This could be achieved by banning the use of road salt on roads and footpaths or by engineering barriers such as the closing of inlets in winter to prevent salt-contaminated water from reaching the root zone [35].

3.5.2. Waterlogging

Waterlogging can reduce tree root growth by causing a lack or absence of oxygen in the soil matrix [65]. To achieve optimal tree health and benefits, technologies and vegetation engineering strategies must prevent the waterlogging of tree pits [47]. Where waterlogging cannot be avoided, e.g., by extremely slow drainage systems or slow infiltration, roots may be submerged for prolonged periods. This can lead to reduced growth and even tree death [32,34,47,66]. Waterlogging is most likely to occur where exfiltration from the tree pit is low, e.g., where base layers are installed over poorly draining clay soils or other impermeable layers that can store significant amounts of water above the clay [14,34]. The technical design of BGI tree pits should allow water to drain within two days to avoid restricting tree root development [46]. However, there are some species that tolerate flooding [32,34,46,66], such as elms, honey locust and London plane [46].

3.5.3. Drought

The high porosity and high infiltration rates of most tree substrates could result in low water availability in BGI tree pits during dry periods [34,43]. In addition, the installation of underdrains (to prevent waterlogging) may lead to drought conditions, especially if the drain is installed next to a highly porous structural soil medium [34]. There may even be a need for additional irrigation to maintain tree health during dry periods [34]. The use of tree species with high ET rates to increase the stormwater management performance of BGI tree pits could exacerbate the problem of drought, threatening tree survival and consequently the volume of runoff that is transpired [18,49]. This is also likely to reduce stormwater treatment performance [65]. Even if the roots are eventually rooted into the surrounding soils (which is desirable), these soils will also experience periods of high and low water availability [18]. It is therefore important to select tree species that have high ET rates when runoff water is available and also have a high sensitivity to drought, i.e., the ability to rapidly down-regulate ET when the tree pit substrates dry out [49]. Tree species with greater stomatal control, especially short-term stomatal closure, will survive prolonged and repeated droughts by conserving substrate moisture and may be more climate resilient if drought duration is predicted to increase in the future [67]. The risk of drought is greatest in systems with limited internal water storage or in climates with infrequent rainfall [49] and can be mitigated by designing systems with more water storage, e.g., with a deeper substrate, more substrate volume or internal water storage created by a raised outlet [50,67,68].

3.5.4. Clogging

Clogging due to high sediment, leaf and debris loads is the most common reason for failure of streetscape stormwater control measures [69]. In a study of a roadside stormwater management system, ref. [41] reported that despite the use of a basket filter, fine sediment and debris could accumulate in the pipes and in the tree trench. This resulted in reduced exfiltration rates [41]. Preventing clogging of various BGI systems with filters may result in reduced retention in certain systems, and therefore alternative inlet designs should be investigated [41]. Therefore, Ref. [41] suggests that the inlet design must be robust to cope with site-specific factors and high sediment and debris loads and must operate in the absence of high-frequency maintenance. Successful engineering solutions are cited, such as removing the curb around bioretention tree pits to allow stormwater to flow as a relatively uniform overland flow along the length of the system [52,68]. Curb cuts can also effectively maintain inflows for street tree pits [70] and are relatively easy to maintain [41,70]. For permeable pavements, the trapping of fine sediments is a beneficial additional function that promotes pollutant removal [71], but this process has also been shown to reduce hydraulic performance over time due to clogging [38,72,73], which could also lead to more frequent maintenance and increased costs [38].

4. Discussion

4.1. Hydrologic Performance

The performance of different systems in terms of rainwater retention and flood prevention depends on several factors. On the one hand, the retention capacity depends on the ratio of the area of the tree pit or its volume to the size of the catchment area [50]. On the other hand, the infiltration rate in the tree pit and the exfiltration rate in the surrounding soils and/or the drainage rate to the sewer system are important factors [34,39]. They are mainly determined by properties such as hydraulic conductivity and maximum water potential of the substrate in the tree pit and the surrounding or underlying soils. Additional storage units such as cisterns can be incorporated to increase the hydrological performance [35]. Where exfiltration rates are sufficiently high, BGI tree systems can provide an alternative approach for increasing urban street tree growth without the expense of installing drainage and connection to the stormwater network [34]. The rate of exfiltration into the underlying soils is therefore a determining factor; in some cases where exfiltration from the tree pit is not suitable, a drainage pipe must be added to ensure drainage and avoid waterlogging [39]. Increased rainwater capture can, in most cases, be achieved by adding a drainage layer or increasing the size of the tree pit [27]. The contribution of tree transpiration to the water balance of BGI tree pits appears to be a positive factor in stormwater management [50]. The effect of established trees was not reported in the studies reviewed, although it is likely to be significant. There is a limited understanding of the potential contribution of established trees to the water balance of BGI tree pit systems, such as through increased transpiration. Analyzing Figure 4, with a mean observation period of 17 months and a mean time from planting to measurement of 27 months, it is clear that long-term observations of these systems are rare. This confirms the statement that there is a need to improve the length and frequency of study interventions and to increase the number of controls used to make a more reliable comparison of the impact of trees on urban hydrology [47]. It is clear that street tree BGI systems have significant potential to reduce the risk of flooding in urban areas. Due to the high variability in system design and size, there is also a high variability in retention performance. Further research and design refinement are therefore required [41].

4.2. Tree Health

Due to their size and rooting volume, trees can have a major impact on the performance of BGI tree systems, and knowledge of tree function in these systems is needed to facilitate this [42]. Studies have shown that BGI tree systems can improve tree growth/health compared to other trees grown on urban soils [31,34], and this in turn can increase canopy cover, which maximizes environmental benefits such as mitigation of the urban heat island effect through evapotranspiration and shading, physiological and economic benefits that trees can provide [34]. A critical factor in growth benefits is waterlogging [34], which must be avoided, as prolonged periods of saturated soils impair tree function, even in highly flood-tolerant species [51]. The choice of tree species for a given site is critical. Various factors, such as size, retention and infiltration capacity of the tree pit, should be considered in order to select species that are well adapted to both the normal patterns and the extremes of the prevailing hydraulic regime [43]. Tree species should also be selected based on their ability to tolerate the unique growing conditions and species-specific preferences (soil type/composition, soil moisture, soil pH, nutrient availability) as well as the stresses associated with urban environments [42]. For BGI systems in climates with infrequent summer rainfall or limited internal water storage, ref. [49] suggests prioritizing drought-avoiding species with high transpiration and rapid transpiration recovery. For systems with more frequent rainfall, internal water storage or consistent access to groundwater, ref. [49] suggests prioritizing higher transpiration rates and recovery in exchange for more moderate drought avoidance. Root volume is another critical factor in mature tree development and performance. Roots in the surrounding soils would therefore be desirable, as many of the BGI systems studied would not provide sufficient rooting space for mature trees. However, it is questionable whether the roots will grow in the less favorable site conditions in the long term. If this is not the case, the rootable tree pit volumes would be fixed. The steeply increasing water demand of trees as they grow means that their dependence on additional water will either have to increase proportionally or growth will have to be restricted [43]. This again confirms the need to improve the duration, frequency and number of studies, in this case to be able to follow long-term root development, possibly from tree pits. Short observation periods must also be viewed critically, as interventions have a limited effect on tree physiology in the first 2 years after planting, when establishing trees are mostly dependent on roots in the root ball [54]. It is important to ensure that roots grow deep, through measures additional to providing high water content in the upper parts of the substrate. Increased water availability directly underneath, e.g., using permeable pavement, encourages shallower rooting, which could have implications for root/infrastructure conflicts and could affect their resilience to climate change due to shifts in rainfall regimes [55]. Increasing the volume of stormwater storage is possible by increasing the volume of tree pits and, for example, incorporating internal water storage via a raised outlet [67,74] and/or outlet control structures [52] to increase the length of time that trees can store water between inflow events [18,52,68]. Water storage elements under the root zones of BGI tree pits, some with capillary water supply in the root zone, are being tested as part of various technical designs under the BlueGreenStreets research project [75,76]. It is still largely unclear how trees will react in the long term to the targeted infiltration of rainwater in BGI tree pits and how much water will be available to the trees, especially during dry periods. Technical options such as additional storage elements are currently being investigated to store water for dry periods and make it available to the trees.

5. Conclusions

With the growing importance of adapting urban areas to the impacts of climate change, there is a tendency to formulate climate adaptation targets for urban development projects to absorb, reduce and regulate water flows and to recycle rainwater for irrigation of urban greenery. Draining rainwater from impervious surfaces into tree pits has considerable potential for stormwater management in terms of local-scale flood prevention, creating a near-natural urban water balance and reducing drought stress in urban trees by passive irrigation. Worldwide efforts to optimize tree pits for rainwater infiltration and water supply show promising approaches. Different vegetation engineering systems and substrate types have been tested for several years, and street trees generally show good vitality, although systematic long-term monitoring of tree vitality has rarely been carried out. There is still a need for research into temporary water storage for dry periods. In light of climate change, with a trend towards more dry periods and drought stress, especially for young trees, different systems should be tested and developed.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16050655/s1, List S1: List of studies identified by systematic review.

Author Contributions: Conceptualization, M.R.; methodology, M.R.; investigation, M.R., K.H. and N.M.; data curation, M.R., K.H. and N.M.; writing—original draft preparation, M.R.; writing—review and editing, M.R, K.H., N.M. and W.D.; visualization, M.R.; supervision, W.D.; project administration, W.D.; funding acquisition, W.D. and M.R. All authors have read and agreed to the published version of the manuscript.

Funding: The research project BlueGreenStreets, under which this study was produced (grant numbers 033W103A and 033W103AN), was funded by the German Federal Ministry for the Education and Research within the Resource-Efficient Urban Districts initiative.

Data Availability Statement: We have shared the identified studies used as primary sources in this article as Supplementary List S1.

Acknowledgments: The authors would like to thank all those who contributed to phase 1 and 2 of the BlueGreenStreets research project.

Conflicts of Interest: The authors declare no conflicts of interest.

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