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Review

Review: Improving the Impact of Plant Science on Urban Planning and Design

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Abstract: Urban planning is a vital process in determining the functionality of future cities. It is predicted that at least two thirds of the world's citizens will reside in towns and cities by the middle of this century, up from one third in the middle of the previous century. Not only is it essential to provide space for work and dwelling, but also for their well-being. Well-being is inextricably linked with the surrounding environment, and natural landscapes have a potent positive effect. For this reason, the inclusion and management of urban green infrastructure has become a topic of increasing scientific interest. Elements of this infrastructure, including green roofs and façades are of growing importance to operators in each stage of the planning, design and construction process in urban areas. Currently, there is a strong recognition that "green is good". Despite the positive recognition of urban greenery, and the concerted efforts to include more of it in cities, greater scientific attention is needed to better understand its role in the urban environment. For example, many solutions are cleverly engineered without giving sufficient consideration to the biology of the vegetation that is used. This review contends that whilst "green is good" is a positive mantra to promote the inclusion of urban greenery, there is a significant opportunity to increase the contribution of plant science to the process of urban planning through both green infrastructure, and biomimicry.

Keywords: biomimicry; plants; architecture; future cities; urban planning

1. Introduction

This review has been approached by considering key environmental parameters which pose opportunities and challenges in the built environment; namely, light, heat, water and carbon dioxide. In each section, the opportunities to use plants in situ, or to learn from them through biomimicry, are discussed in relation to an over-arching question. Current research regarding the ability of urban environments to respond to the challenges posed by fluctuations in these environmental parameters is then discussed and opportunities for interdisciplinary learning between plant science and building related disciplines are presented.

Green space has long been associated with well-being. Plants in cities provide us colour and character in our streets, and a range of ecosystem services such as shading, cooling, control of storm water run-off, and CO_2 fixation. Cities are efficient in their provision of infrastructure and public services as well as a concentration of opportunities for employment, business and inter-personal relationships. As a result, urban centres are growing around the globe, and it has been predicted that more than 70% of the human population will live in one by the year 2050 [1]. As urbanisation increases globally, we need our urban plants to do more than decorate the city. Plants being sessile are highly capable of successful environmental adaptation, including tolerance to extremes of heat, light, water and CO_2.

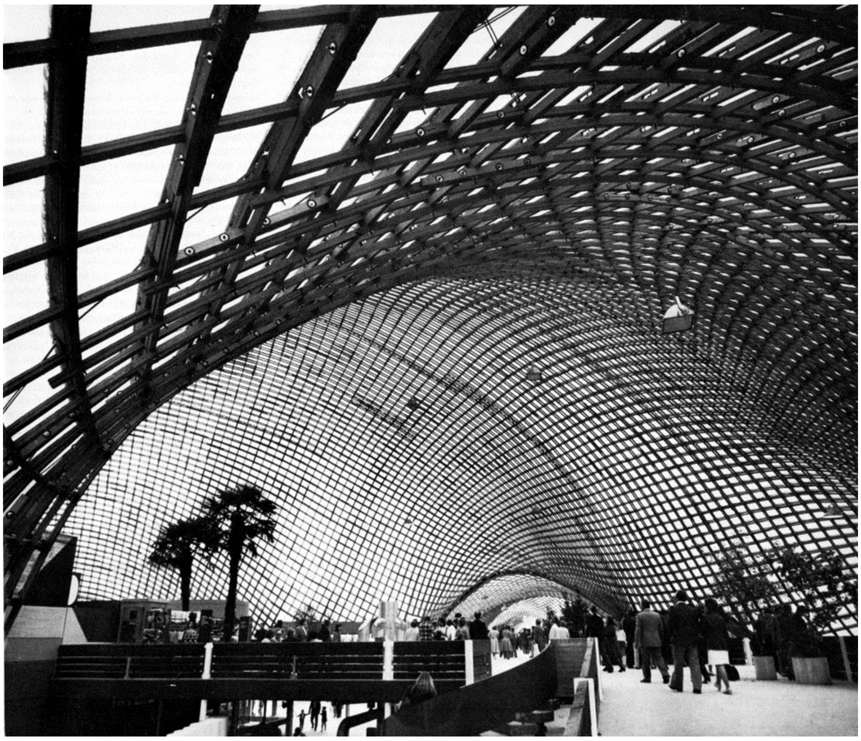
Plant science has traditionally sought to understand the biology of plants and to exploit this through agriculture and horticulture. Increasingly, however, the expertise of plant scientists is also likely to be important for the growing of plants in new environments and for design inspiration. Plants can therefore provide both direct and indirect solutions, the latter through biomimicry. Plants can help to provide thermal comfort, energy savings, storm water mitigation or carbon sequestration in urban environments. A better knowledge of how green spaces interact with the built environment, and how people utilise them is vital to maximising the health and wellbeing of those living in the city. The diversity, and longevity of functional ecosystems within a city which require little maintenance and provide a greater range of ecosystem services will be vital to the success of urban greening schemes. In Europe and the US, the integration of plants into urban environments is being led by urban planners and policy makers where there is a strong recognition of the importance of green space [2–4]. Thus far, the consideration of how to incorporate plants into many urban settings on a large scale could be characterised as "green is good", with less consideration given to precisely what kind of green is best. Ecological research has had a significant impact on the use of plants in the urban environment for example in the promotion of biodiversity [5–8] and in terms of biological suitability [9]. Meanwhile, there is a need for a greater contribution from plant scientists in the evaluation of which plant should be used for each given function and how plants respond biologically, to the challenges that urban environments pose such as increased heat, highly transient drought and flooding events and elevated CO_2.

1.1. Introduction to Biomimicry

The mimicry of natural forms is not a new concept. Biomimicry as a discipline has been pioneered by visionary scientists who have promoted its values in their popular works [10,11]. Plant forms have provided the inspiration for several biomimetic designs such as Velcro (inspired by the properties of burdock burrs), or the regular nodes of Bamboo (which divide its stem into strong hollow sections) that inspired the hex-tri-hex design of the Eden Project [11]. Plants and natural shapes in general have also inspired architects and engineers like Antoni Gaudi (1852–1926), Felix Candela (1910–1997) and Frei Otto (1925–2015) to create beautiful, multi-functional buildings [12], examples are shown in Figure 1. However, in the case of mass urbanisation, building design has mostly served to fulfil only the most immediate functions. A reductionist approach to city functionality is merited in the sense that buildings must be fit for purpose, but it tends to neglect the idea that a building may have many purposes in its lifetime and may influence the surrounding infrastructure in ways which are different from what was originally conceived. Take for example the canopy of a forest, perhaps the most analogous to the density of the urban built environment. From above, it appears contiguous, but from below multiple layers can be seen. These layers help to maximise the use of resources that could not be captured by a single canopy layer. The trees and plants which cooperate in a forest ecosystem are each adapted to maximise their advantage in their individual ecological niche, not all trying to serve the same purpose. As they grow, their position and purpose within the ecosystem changes and shifts to adapt to a new set of environmental stressors. This plasticity is at the heart of plant success. The ideal form of a building, therefore, cannot be viewed in isolation but instead relies on the forms and environments that surround it. In this way, borrowing from plants to design the form of buildings (or the materials therein) is not simply the idea of replicating a leaf or plant shape that offers structural or energy efficiency advantages, but rather about determining the form which can best occupy the available niche, to the mutual benefit of the ecosystem. In the design of a new city, the combination of forms can be modelled, planned and executed to provide a variety of advantages [13,14]. In the case of existing or developing cities, the process by which plants are organised is perhaps a better model for how best to locate and design new buildings, or indeed to restore old ones. Both plants and buildings are sessile and must therefore cope and adapt to the prevailing environmental conditions, the interface between the two, therefore, being a fertile ground for study and innovation. Additionally, perennial plants, which must tolerate, and be resilient to, all seasons through multiple years, including the occurrence of extreme weather events, provide the potential for learning alongside annual plants which exploit favourable conditions.

(**a**)

(**b**)



(**c**)

Figure 1. (**a**) The interior of the basilica at La Sagrada Famiglia. Designed by Antoni Gaudi. © Cyril Bays. (**b**) The interior of Los Manantiales Restaurant, Mexico. Designed by Felix Candela. © www.rkett.com. (**c**) An interior view of the Manheim Multihalle. Designed by Frei Otto.

The environmental stressors faced by plants in urban environments include light, heat, carbon dioxide (and other air constituents), humidity, temperature, wind, water and nutrition [15,16]. These stressors are similar to those which human city dwellers are increasingly being affected by as a result of urbanisation. Table 1, adapted from Pedersen Zari [17], shows how the emulation of natural plant forms in the built environment can be considered on several scales; organism (mimicking a specific organism), behaviour (mimicking patterns of behaviour) and ecosystem (mimicking inter-dependent relationships at an ecosystem scale). To expand this organisational structure further, and consider all of the buildings within a city as individual plants within an ecosystem, it may be possible to simulate or model the evolution of the city using biological principles including survival and adaptation. This type of simulation could allow us to visualise how elements of city architecture interact to have positive or negative effects on the overall functioning of the city ecosystem from a biological perspective. The findings from such a simulation could inform opportunities for reorganisation, re-development of districts, or new building projects to promote more optimal symbiotic interactions between building forms to the benefit of overall energy resource use. Green spaces could also be isolated and modelled using advanced remote sensing (drone technology, etc.) and hyperspectral imaging techniques to uncover their interactions with the environment, giving fresh understanding as to where and how to incorporate plants and other greenery to maximise their impacts. Our ability to construct technological solutions to complex energy problems is considerably advanced, and will no doubt continue to advance, but we must be aware of whole-system functionality in order to deploy technology in the most advantageous ways, not simply for the benefit of one building or its occupants, but for the wider ecosystem.

Table 1. A framework for the application of biomimicry (adapted with permission from Pedersen Zari, 2007 [17].

Level of Biomimicry	Examples—Buildings that Mimic Plants	
Organism Level (mimicry of a specific organism)	Form	A large span building that looks like an Amazonian water lily.
	Material	A building made directly from timber, or from materials that mimic its properties.
	Construction	The building is made in the same way as a plant, with nodes acting as stiffening "bulk heads" as in bamboo for example.
	Process	The window adornments adjust depending on the angle of the sun, as in heliotropism.
	Function	The building acts as a plant would in a wider context, cycling water or increasing heat loss on hot days.
Behaviour Level (mimicry of how an organism behaves or relates to its larger context)	Form	An adaptive shading canopy that extends or retracts like a convolvulus flower.
	Material	A material that allows the building to move and flex in the same way that plant stems such as willow do.
	Construction	A building that is built in the same way as a plant grows, wide anchoring base like roots, or single hollow stem such as bamboo.
	Process	The building operates as a plant would; by careful orientation, adaptive cooling, etc.
	Function	The building functions as if it were a plant, stable internal environment, water conservation, "dormancy" in winter, etc.
Ecosystem Level (mimicry of an ecosystem)	Form	A building which resembles several trees or plants in close proximity.
	Material	A collection of buildings made from natural materials found in a natural ecosystem. Using limecrete/hempcrete, etc.
	Construction	The buildings are assembled in the same way that a forest is, with multiple canopy layers and buildings occupying different niches.
	Process	The building acts as a forest would, capturing and converting solar energy and intercepting and storing/transpiring water for example.
	Function	The building is able to function as a tree would in a forest, recycling waste, interacting with other organisms, participating in hydrological cycle.

1.2. Introduction to the Integration of Plant Science and Urban Design

Both plants and cities are subject to variation in multiple environmental factors including light, heat, air composition, wind and water. It is desirable for buildings to adapt to multiple stressors caused by extremes of these factors either sequentially or concurrently, mimicking the strategies of plants. The diversity of plant species is a result of conditions such as competition, environmental stress and predation (amongst others) which together create a driver towards species evolution and adaptation. Buildings too must conform to increasing standards of environmental efficiency, typified by recent energy efficient building designs such as Passivhaus pioneered in Germany [18] or the "One Planet Living" concept pioneered in London [19]. One difference between cities and natural ecosystems is replication. In terms of form, no two trees in a forest are alike because each is challenged by a subtly different set of environmental pressures. However, the way they organise their internal structures is more uniform. They each have the same capabilities, but the way they deploy them is more reactionary. In the built environment, we need to look to forms which can be widely replicated, yet will respond/adapt to their specific location and environment. In future cities, we can seek to emulate the diversity of a natural ecosystem by recognising where nature's solutions can be replicated using technology and advanced materials to mimic the actions of plants. For example, increasing density (such as tower block living) is often considered as a method for increasing resource efficiency and sustainability (energy, water, materials, transport, infrastructure, etc.) in urban environments, particularly when cost or space usage are considered as the "efficiency" variable. However, high density developments also imply a loss of daylight, increased requirements for electric lighting [20], a loss of green space and drainage problems (e.g., sponge city [21], the negative psychological issues surrounding high density living [22] and a difficulty in integrating renewable energy [23]). Plant communities are examples of a "systems" approach to efficiency and sustainability, in that the interactions and interdependence between their components are measures of their success rather than their individual elements in isolation. For example, the position and orientation of a plant has profound implications on the plants around it, and they respond accordingly. Plants form a complex network though their mutualistic interactions with for example; microbes [24], endophytic fungi [25], insects [24,26] and each other [27], allowing them to understand the environment that they are adapting to. This is a concept that can be replicated in cities by, for example, better understanding the impacts of green spaces on the buildings around them, or by thinking about the changes in operating parameters that will be brought to bear on a building when another is built or modified beside it. Mimicking these interactions could prevent unintended consequences such as wind tunnels/vortices in cities, or shading of one building by another which augments energy use.

Plant science can also share modelling insights that could help urban planners to study the relationships between city components in relation to abiotic stressors, within a dynamic system. For example, elements of functional-structural plant models can be applied to adjust city wide planning models that incorporate building or infrastructure morphology such as the integrated weather research and forecasting system which takes into account building morphology in its prediction of city wide effects of environmental impacts [28]. One of the key features of functional-structural plant models is that each model begins with the identification of the topological body plan of the plant (related to Halle and colleagues' 23 architectural tree models [29]) noting each "organ" and its connections. Similarly, the local climate zone method tool, developed for climatological studies, divides cities spatially into 10 urban types [30]. This method has been incorporated into the larger World Urban Database and Access Portal Tools project which utilises remote sensing and crowdsourcing to better understand the impacts of different urban morphologies [31,32]. By recognising the commonality of "architecture" between the disciplines, and that standardised units of geometry are applied in both, it may be possible to apply the tools of plant science and architecture to each other. Treating buildings in a city as plants in a field may uncover interesting co-dependencies and inter-individual effects which could point to new, more efficient urban building patterns. Meanwhile, treating crops as buildings in a landscape may help to uncover new targets for increasing resource use efficiency.

Existing infrastructure should also not be ignored and new technologies and approaches will need to be retroactively fitted to buildings so that benefits can be achieved more rapidly and more equitably. Retro-fit is therefore an opportunity and challenge, with the potential for short-term benefits that may prove crucial for improvement in performance of future cities and their environments [33].

Urban greening is a term that has been applied to the practice of utilising plants in towns and cities (particularly on a retro-fit basis) (Figure 2). Plants may be able to provide the "systems plasticity" that is lacking in the more rigid build environment, and provide a biomimetic solution through their direct application. For example, a green façade may cool a building during the heat of summer through shading and evapotranspiration, and then provide additional insulation during winter, reducing the fluctuation in indoor temperature and improving thermal comfort. Urban greening includes parks and gardens, avenue planting, green roofs/façades and indoor gardens. Each example often includes elements of both agriculture and horticulture, and crosses descriptive boundaries such as extensive and intensive or urban and peri-urban. The methods that have been proposed and initiated for the direct use of plants on buildings in towns and cities are discussed in relation to the broad environmental stressors that affect city functionality.

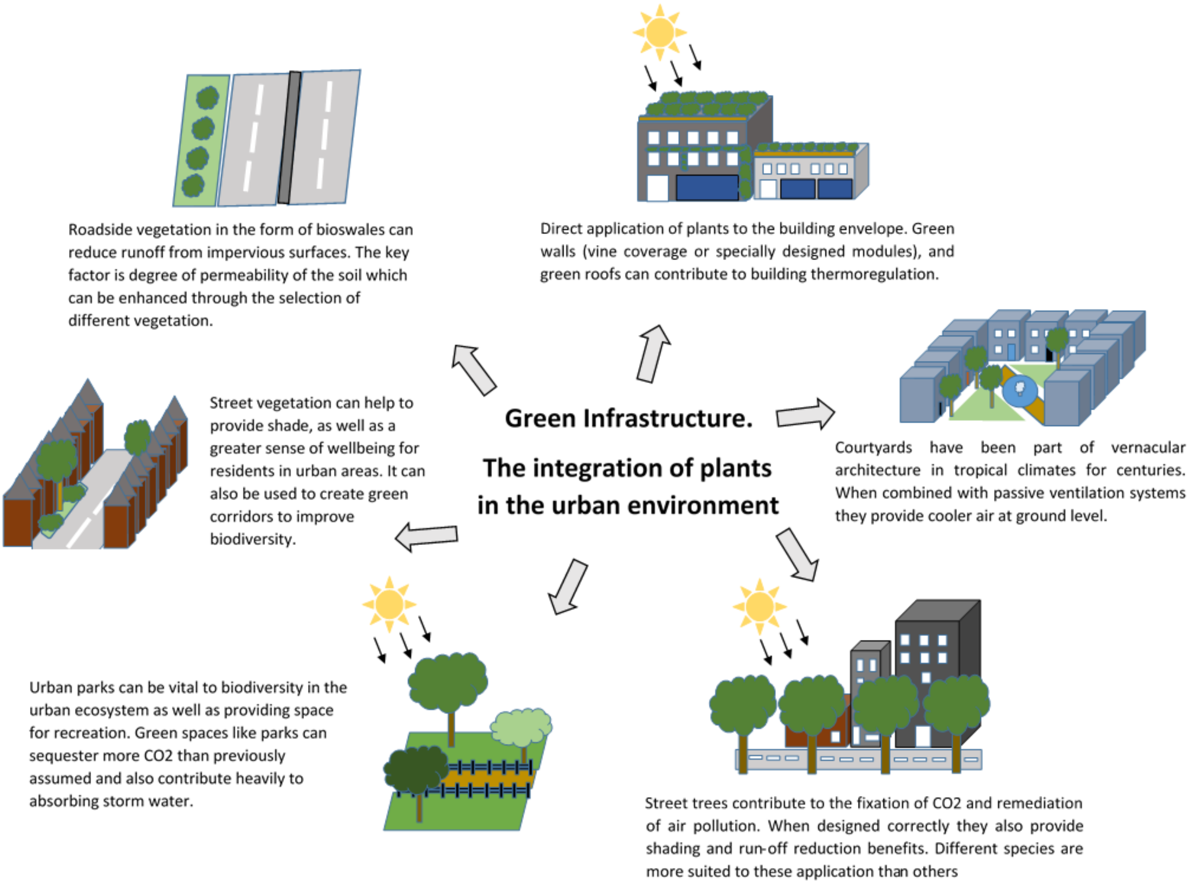


Figure 2. Examples of urban green infrastructure and their potential contributions to the health and wellbeing of urban dwellers.

2. How Can We Utilise Plants' Adaptations for Light Capture, Use, and Avoidance in Urban Design?

2.1. Light Capture

Approximately 1.3 KW·m^{-2} of radiant energy from the sun reaches the Earth, with some variation over the past 400 years [34]. The key considerations therefore are when to intercept light and when not to, how much to intercept, and what to do with it once you have intercepted it. Buildings need to incorporate enough light to illuminate the interior spaces and reduce the need for powered lighting and deliver thermal energy to surfaces. There are therefore limits within which intercepted irradiance generates appropriate light and temperature to provide comfortable living and working spaces. As photoautotrophs, plants need to gather light of the appropriate wavelengths to drive photosynthesis, and intercept a sufficiency of such light for optimal carbon fixation whilst preventing the deleterious effects of photoinhibition and reactive oxygen species (ROS) production. When light capture is determined in building design, thought is placed upon the provision of light to interior spaces, as well as the dimensions and positions of transparent surfaces for visual impact, thermoregulation and noise reduction. Fenestration is a multi-stage process whereby provisions are made for glare, seasonal control of light penetration (according to angle), the consistency of light across a room (light uniformity), and heat loss/gain. Such adjustments are made more precisely for advanced thermo-regulative design such as Passivhaus and other building technologies [35]. There is an opportunity for plant scientists to share knowledge with architects about how different plant forms use light under different environmental conditions and for varying purposes. In terms of form, the main adaptations plants have to their light interception requirements are leaf area, angle, orientation and senescence. Leaves are to plants what the transparent surfaces of a building envelope are to a building [36].

Plants predominantly absorb the wavelengths required for photosynthesis, namely the range 400–700 nm (blue-red). Chlorophyll, the main pigment responsible for absorption of light in plants, has peaks of absorption for red and blue wavelengths, leaving green light to be transmitted through the plant or reflected, giving the plant its colour. Selective light transmitting surfaces have applications in the urban design, wherein "smart windows" have been designed to exclude certain wavelengths to improve thermal management or light penetration [37]. Controlling such windows relies on electrically stimulated changes in material properties (electrochromic smart glass), whereas plants are able to control this using only incident light and could provide the inspiration for how to better control passive solutions such as thermochromic or photochromic smart glass which currently have only a "transition state". This is perhaps more closely mimicked in innovations such as PV controlled shading devices. Plants also adjust light absorption based on the arrangement of their internal structures. The epidermis (leaf surface) cells themselves are typically transparent to allow light penetration, and convex in order to focus light, especially important in low light environments [38].

Below the surface of the leaf, there are palisade cells and the spongy mesophyll which contain light harvesting chloroplasts. The palisade cells appear as columns, 1–3 rows deep. As well as intercepting light to be absorbed, the palisade cells channel light to the layers below, according to their orientation in much the same way that skylights or light wells do in buildings. It has been possible to create light channelling window panels which follow similar principles [39]. Furthermore, since chloroplasts are not uniformly distributed within the palisade cells, they also act as a light "sieve" absorbing a proportion of the light but allowing some to be transmitted below. The proportion that is absorbed is maximised because chloroplasts have a high surface area to volume ratio [40], adding to the sieve effect. Building envelope layers can be arranged in similar ways, being selectively permeable to light according to the incident radiation and indoor comfort requirements. Palisade cells can adjust their orientation to absorb more or less light, arranging themselves either horizontally or perpendicularly according to light intensity. This strategy is reflected in dynamic materials which adjust their orientation/opacity according to light intensity/requirements. In extreme environments where incident radiation is so intense that it could damage plant leaves, they have developed coatings such as waxes, hairs and salt glands which can reduce light absorption by up to 40% [41]. Under the most extreme environments, plants exhibit highly modified structures, such as those exhibited by cacti, where leaves are reduced to spines and ridges increasing shading and reducing water loss. Inspiration from some plant adaptations are already evident in coated window and building panels.

Leaf angle and orientation affect the light which falls on the surface of the leaf, and how much passes to the lower leaves or the ground below. There is a similarity between the consideration of leaf angle and orientation in a plant and the inclusion of differently shaped and oriented windows in buildings. For example, a deep splayed reveal with the window on the inner side results in a reduction in penetration of summer sun and a heat gain in winter when the angle of the sun is lower. A tall narrow window and a short wide window have very different light penetration and thermodynamic properties. Skylights for example, result in a much higher light penetration per unit area than windows placed on the outside of the building. The arrangement of window shapes and positions bears resemblance to canopy architecture, in that whole plant architecture determines light interception [42]. Modern plant science seeks to produce crops with architectures that intercept more light to drive higher rates of photosynthesis and yield [43,44]. The design principles that are used for a crop canopy to increase or decrease light interception can be thought of as analogous to skylight or roof window design in architecture where the aim is also to either increase or decrease the amount of light which falls into the spaces below.

Such interdisciplinary and biomimetic thinking could also be fruitful in reverse by understanding how an architect might design a surface to maximise light interception across a day, taking into account the changing angle of the sun, etc. This is a design task which would not normally be performed since there is always a need for a balance between light interception and light penetration in building design. However, in plant science there is a need to understand how to optimise light interception in order to drive yield gains in domesticated crops. The biggest single determinant of yield is photosynthesis [45], and one major driver for photosynthesis is light interception [46]. Light interception is affected by the canopy architecture (the sum of all the plants in field or all the leaves on a plant, depending on scale). Light interception is in balance with a number of other factors in the plant, such as water availability, gas exchange, and herbivory [47–49], and therefore leaves can be seen as adapted to environments that include light, rather than optimised for light interception. Eighty-five per cent of raw light interception efficiency in plants is determined by two variables; crown density (ratio of leaf area to total crown surface area) and leaf dispersion (the total aggregation of leaves). As leaf number and area decreases, so light interception is reduced [42]. The differences in light interception between plant species can be largely explained by altered dispersion via variations in the leaf number, shape and orientation [42]. These variables are regulated by plants as adaptations to varying amounts of light and water in their geographic region of origin [45,47] and will also change over the lifecycle of the plant with the leaves of the mature plant differing to those of the juvenile. The future proofing of buildings against changes in environmental parameters, but also their use and function, is an important issue in urban planning. The mimicry of plants' adaptability to their environment could take the form of understanding the way buildings respond to changes in the environment over-time, and increasing awareness of the evolution of urban environments. Through this approach it may be possible to take a more sophisticated approach to building evolution at the point of design, or re-design.

2.2. Solar Tracking

A number of plant species are also capable of solar tracking. That is that they move and adapt their position in relation to the sun in order to capture more light (diaheliotropism) or in order to avoid it (paraheliotropism) [50]. The leaves of plants such as lupines (*Lupinus* sp.), and beans (*Glycine max*, etc.) make many small adjustments to their leaf blades (laminae) in response to the light environment. These leaves initiate their movements with the advent of sunshine and are able to pause during periods of cloud cover and re-orientate when the sun reappears [51]. Under stress conditions, paraheliotropic leaves can very tightly regulate the amount of light that they intercept, a concept that has inspired climate adaptive building skins which are able to adjust the amount of light, and therefore heat that is incident on their surfaces [52–54]. In plants, heliotropism is closely related to water availability, since the mechanics of movement rely on internal changes in turgor pressure and air temperature [55]. It is an energy efficient process driven by water potential gradients. Therefore, both the principle of movement and the mechanical efficiency by which it is achieved are examples of opportunities for biomimicry in architecture, whereby innovative hydraulic solutions are being tested [54] and potential exists for energy efficient solutions derived from plants.

2.3. Light Avoidance

As a result of their need to capture light on the upper surface, leaves are also, by extension well designed to provide different levels of shade below. Leaves provide varying levels of shade depending on their survival strategies. Many plant species, such as dandelions (*Taraxacum* sp.), grow close to the soil, whereby their leaves all but shut out light to the ground, smothering any attempt by other plants to gain a foothold. Others such as nettles (*Urtica* sp.) and ivy (*Hedera* sp.), arrange their leaves in tessellating patterns to allow maximum light capture by each layer of their own canopy, but to prevent any light reaching the ground. Plants such as soybeans (*Glycine max*), are also capable of specific movements such as heliotropism, bending, folding or even volumetric flexibility in order to change the amounts of absorbed light according to surrounding conditions. The spatial arrangement, shape, orientation/inclination and dynamic movement abilities of plants make them an ideal source of inspiration for shading applications as illustrated in Figure 3 [36]. Mimicry of these abilities is of continued interest [53,56,57], and the adaptability of shading devices is of paramount importance in order to justify their expense, warranting further investigation. Plants can also be applied directly to provide shading in urban environments. There are two main areas in which this is common; to walls and walkways attached to a building envelope, and as trees surrounding or surrounded by buildings. In both, the aim is to reduce or control the amount of light incident upon a surface and by so doing, to improve the comfort of the space for users or to improve the functionality of the building. Vines and climbers have often been used on covered walkways and small shelters to provide shade, and their application around windows and even on roofs to provide a dense canopy of shade presents a number of opportunities for city greening. Climbing plants have the advantages of being able to cover a wide surface area owing to their rapid and extensive growth. Using lightweight wire frames and strategically placed planters, vines have the potential to be used in a wide range of retro-fit scenarios to provide shade, slow down storm water, trap particulates, and improve building thermoregulation.

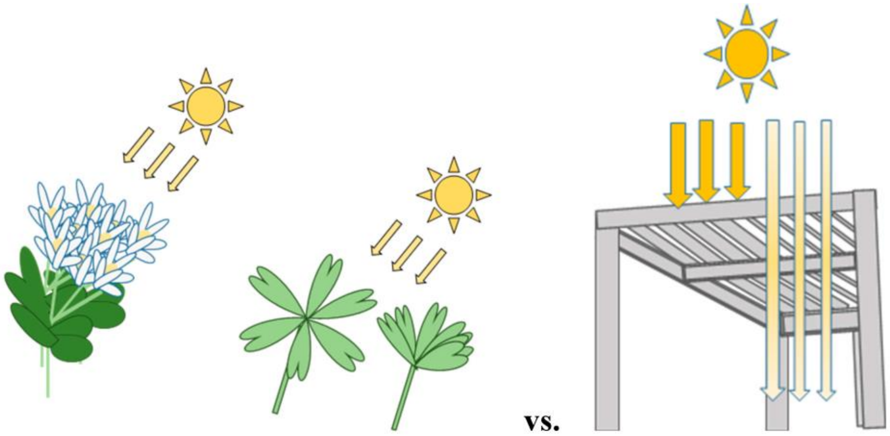


Figure 3. Example of responses for diaheliotropic and paraheliotropic plants and their relationship to adaptive shaping. Examples include bending of whole plant towards sun, orientation of leaves to either capture or avoid sunlight and an adaptive shading terrace whereby slats open to allow a portion of light to reach the ground.

2.4. Light Modelling

In a field of crops, the architecture of the whole canopy is considered in order to understand resource use and productivity. Plants such as wheat (*Triticum* sp.), maize (*Zea mays*) and other staple food crops are grown at high density in order to maximise yield. In the field, each plant is affected by, and responds to, neighbouring plants. A major opportunity to increase crop yield is, therefore, to find crop ideotypes which effectively tessellate when they are grown in close proximity to one another to maximise light interception, photosynthesis and yield [46]. The aboveground leaves and stems intercept light, but the belowground roots are also important. The roots of different plants also interact with other organisms in close proximity as well as competing for water and nutrients needed for the growth and survival of the plant [58]. Earlier research in this field focused on understanding light interception using process-based static models where computational models estimated crop growth, driven by light interception, and consideration of the growth rates of individual components such as leaves, stems, etc. [59–61]. More recent analyses are utilising functional-structural plant models to allow for the effects of each plant on neighbouring plants, thus treating the crop canopy as the sum of each individual plant [62]. Functional-structural plant models reflect the 3D structure of plants that describe their development over time based on physiological drivers, which in turn are determined by environmental parameters [63]. This approach allows links to be made between how individual plants function, and crop performance in the field. In addition, relationships between form and function both at the plant and canopy level can be elucidated. A field of crops is roughly analogous to a city of buildings, in as much as there are interactive effects between the individual components. There is a considerable similarity between the types of modelling that are conducted in order to connect form and function between plant science and urban planning. These similarities represent an opportunity to apply methods from each discipline to the problems presented by the other, in order to stimulate innovation.

3. How Can We Use Plants Adaptations to Mitigate Undesirable Temperature Fluctuations?

The challenges of heating and cooling both buildings and cities in relation to thermoregulation and the urban heat island effect can also benefit from plant science. Building thermoregulation refers to the ability to regulate internal temperature regardless of the prevailing environmental conditions. Urban heat island refers to the phenomenon of higher recorded temperatures within a city compared to the surrounding suburbs and countryside.

3.1. Thermoregulation

The building envelope is a target for improvements in building thermoregulation. In temperate regions with warm summers and cold winters, buildings need to perform according to the season. In tropical and arid regions the challenge is to maintain a comfortable relative humidity and reduce the need for active cooling, whilst in cold regions there is a requirement for enhanced insulation and heat conservation. The incident light on a leaf in full sun requires the exposed plant to dissipate a great deal of heat. Similarly, under full sun, the heat gain to a building can be considerable and result in uncomfortable indoor conditions. Leaves dissipate heat through radiative losses of long wavelengths, sensible heat loss through convection, and latent heat loss through evaporative cooling. The ratio between the latter two cooling methods is referred to as the Bowen ratio [64], and finding ways to utilise each of its constituents in intelligent building design represents an opportunity for a biomimetic solution. The adaptive building envelope, or climate adaptive building shell is a design concept which is being re-implemented, with the aim of increasing latent heat loss when indoor temperatures are too high, and maintaining insulation and thermal comfort when the temperature falls. The field of climate adapted buildings has diverged in to active technologies and passive design [52]. Climate-adapted building shells offer a step change in the efficiency of buildings and to develop interiors that utilise natural forces to drive changes in user comfort. The field is not yet fully developed and there is considerable scope to utilise biologically derived adaptation strategies to drive innovations such as the Cabo Llanos Tower in Tenerife and the Singapore Arts Centre, which both incorporate learning from plants to create shading solutions for the prevention of heat gain [11].

Humidity is strongly influenced by thermal regulation [65], particularly in hot and humid environments [66]. Plants such as street trees, green roofs/façades or houseplants, can have a significant and direct impact on humidity in the urban environment. For example, plants increase the moisture content of the indoor environment [67]. When water is available, plant transpiration increases with heat, and subsequently increases the amount of water vapour in the air. The effect of vegetation on thermal comfort can be either positive or negative depending on whether the prevailing climate is humid or dry [68]. In the plant, transpiration rate is driven by the difference in water vapour concentration between the leaf and the surrounding air mass and regulated by stomata [69,70]. The effect of urban environments on plants can likewise be positive or negative. Plants could be deployed in building design wherever there is a need to increase humidity, as long as the plant itself is not subjected to excessive heat stress, generally avoided through sufficient irrigation. Wang et al. [68] provide a more detailed review of the effect of green infrastructure on the indoor environment. A key feature of plant leaves to achieve temperature regulation are the stomata, which continually respond to external stimuli and internal signalling and again provide an opportunity for learning from plants. A review of plant inspired adaptive materials is provided by Lopez et al. [71].

3.2. Green Coverings and Thermoregulation

Applying plants directly to the building envelope can be a cost effective solution for retrofit projects and is increasingly being specified for new buildings, where they can be applied either as a roof or a façade. Both green roofs and façades have been advocated as potential solutions for improved building thermoregulation because they block and reflect light leading to reduced heat gain. The layers of substrate and plants may also offer additional insulation, retaining heat during colder periods. The selection of plants for green roofs and façades may be as important to their performance as other elements of their design. Castleton et al. [72] noted in their review of green roof benefits, that a greater focus on plant type and substrate was needed. In the green roof industry plant selection choice tends to range from extensive to intensive based on the depth of substrate. Extensive green roofs are those with a substrate depth of <150 mm, semi-intensive roofs range from 150–250 mm and intensive roofs will have a substrate depth of above 250 mm. Common choices for extensive roofs are Sedum species (*Sedum* sp.—e.g., *Sedum acre*) which exhibit crassulacean acid metabolism (CAM), a modification to photosynthesis and adaptation to extremely dry conditions [73]. Pre-grown mats of sedum are routinely used for large scale roofs, but whether or not these mats deliver improved building thermoregulation is not clear. Indeed, the benefit of a green roof in terms of insulation is unclear. If the building, and particularly the roof, is well insulated to begin with (as in a Passivhaus) then the need for additional insulation is negligible. As an example the U value for materials in the "thermal envelope" of Passivhaus buildings is typically <0.15 W/M^2K [74] whereas the U value of a typical green roof is 1.73–1.99 W/M^2K [75]. Additionally, in winter when insulation needs are greatest, plant growth, especially of sedum, is at its lowest. However, for old buildings and buildings where improving internal insulation is difficult, there may be benefit to fitting a green roof [75]. The U values of non-insulated roofs have been reported as 7.76 W/M^2K (with 25 cm of concrete) to 18.18 W/M^2K (with 10 cm concrete), therefore the green roof could reduce the U value of a non-insulated roof by between 6 and 16 W/M^2K [75]. In such circumstances the density of the planting (leaf area index) and depth of substrate are each additive to the benefit, although cost increases with substrate depth.

3.3. Passive Cooling and Urban Heat Island Mitigation

Transpiration by plants can be used as a strategy for cooling air, since hot air is cooled as it combines with water and evaporates. As long as plants have an adequate supply of water and nutrients, they will continue to transpire, cooling the air around them. This, together with albedo, is the believed basis for the cooling effect of green roofs on Urban Heat Island (Figure 4). This strategy can also be used as a means of generating cool air for passive ventilation systems such as stack ventilation [77]. In such a system a sunken courtyard, protected from the sun is created at the centre of a building and planted with shade tolerant species (fountains have also been used). As they transpire, the plants cool the air, which is then drawn through the building by a pressure gradient (warm air rising), eventually being released as heated air at the roof. This strategy is especially popular in arid climates, where cooling of buildings represents both a challenge and cost [78]. Courtyards have been an important part of vernacular architecture in hot and arid climates for centuries and represent an environmentally positive method for providing thermal comfort [79]. Such strategies are now being re-visited with the renewed interest in passive cooling strategies [80,81].

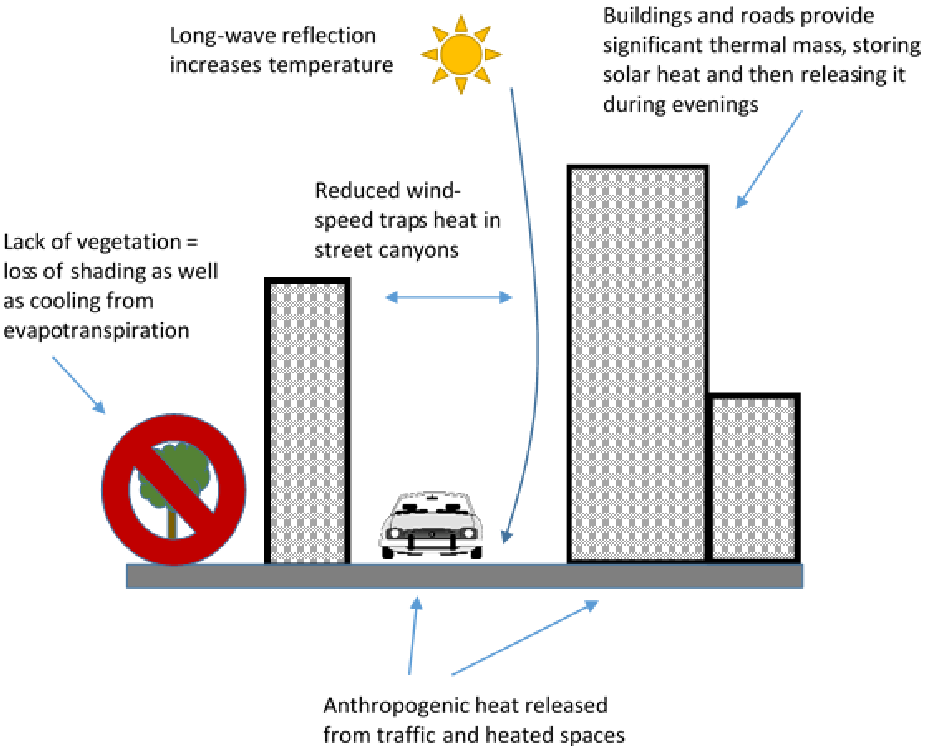


Figure 4. Contributions to Urban Heat Island (UHI) from multiple sources, including a lack of vegetative cover and reduced evapotranspiration.

Plant selection may be far more crucial when it comes to limiting heat gain to a building and cooling the outdoor temperature. When dark-coloured roofs (especially bitumen) are exposed to direct sun, the surface can reach extremely high temperatures, perhaps in excess of 70 °C in some cases. This has profound implications for the amount of heat that is returned to the atmosphere as well as the lifetime of roof surfaces and building heat gain. Furthermore, vegetation on a building has the challenge of heat stress from above (sun) and below (building heating). The variation in energy flux and solar transmittance has been assessed for vegetated roof vs. standard roof/cool roof and for different substrates in a number of studies [82,83] although none have so far considered the contribution of internal heat production. Modelling studies have also showed that green roofs are dynamic, according to the growth of the vegetation throughout the seasons, and that a large number of parameters are relevant in estimating their thermal performance and UHI mitigation potential [84,85]. The specific plant parameters of greatest consequence are reported to be leaf area index, vertical canopy thickness and total vegetation coverage. The models that have been proposed have been considered too complicated to apply in practice, at scale, because they require detailed parameterisation [86]. However, the greater ecological imprint of green roofs as novel ecosystems, and the impacts that the functionality of the ecosystem has on the overall ability of the green roof to perform have been highlighted as an area where research and development should focus [87], with the diversity of species and thus function being a particularly strong driver [88]. In terms of land cover, greenery can reduce temperatures. In a large scale study of UHI effects according to land use type in Toronto, Rinner and Hussain [89] found that green land had a significantly lower average temperature than commercial/industrial land. Furthermore, in a recent review by Santamouris [90], modelling data applied at the "whole city" scale showed that green roofs could decrease temperature 0.3–3 °C if widely deployed. In such a scenario evaporative transpiration from plants may account for up to 30% of total cooling [91,92]. The consideration of evapotranspiration in the planning and design phases of green building envelopes is therefore warranted, and could yield improved economic viability. The breeding of plant species to optimise functionality in terms of combining stress tolerance with coverage, biodiversity and, to a lesser extent, aesthetic value for green roofs and façades is a rich opportunity in plant science, and could provide more accurate guidance on how to resolve the conflict between the long-term benefits of a complex planting system with the short-term costs of its installation.

4. How Can We Utilise Plants to Improve the Management of Water in Urban Environments?

In the built environment, the management of water concerns managing water quantity and managing water quality (not discussed here). There has been a gradual modification of the landscape as cities have developed and expanded, and this has resulted in changes to the way the landscape interacts with the local water cycle [93]. In many cases, developments have occurred without sufficient consideration as to how the water cycle will be affected (Figure 5). These effects on the water cycle then result in two main threats, both to people and the wider ecosystem: floods and drought. The problems associated with water, for which plants may yield solutions, are therefore divided according to those which occur as a result of water moving through the environment (water quantity) and what that water picks up on the way (water quality). Surface water flooding events are becoming more common, and more damaging with the increased frequency of extreme weather events [94,95]. The replacement of natural ecosystems with impermeable surfaces has meant that water is not able to disperse, and is instead channelled into drains. Inevitably, this creates bottlenecks during storm events and results in the surface water floods that have been so often documented. Furthermore, when large quantities of channelled water enters water courses, the effects on downstream flooding can also be considerable. Improved surface water drainage systems for urban areas are a priority for urban planners, researchers and policy makers [96–98]. The incorporation of planted areas into the built environment is incentivised by the Building research establishment's environmental assessment method (BREEAM), and credits can be obtained by installing green roofs and further permeable surfaces as sustainable urban drainage (SuDs) techniques under category POL03 (Surface water run-off) of the BREEAM code, which is used to assess the environmental sustainability of building projects [99].

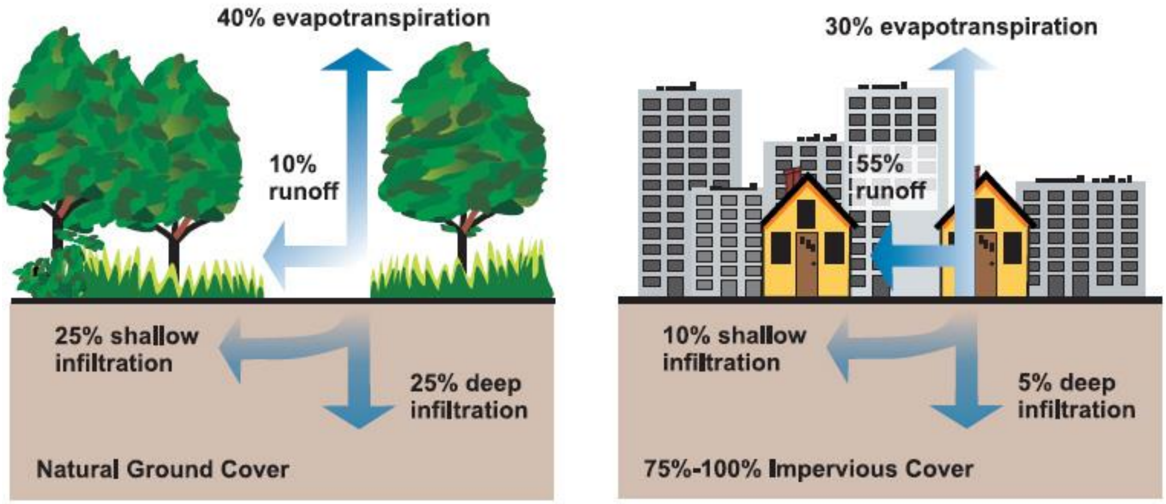


Figure 5. Water cycle comparison of urban and natural landscapes. Reproduced from US Environmental Protection Agency Doc. No: EPA 841-F-03-003 [99]

Buildings and plants both impact upon the water cycle. Plants need to balance water uptake and loss from the growing medium to support metabolic processes, biomass expansion and to maintain cellular volume, and so affect the flow of water between the atmosphere and the biosphere through uptake and transpiration. Similarly, buildings affect the flow of water through the environment because they are traditionally solid, impervious surfaces and surrounded by similarly impermeable surfaces at street level. Once again a city of buildings can be considered as a canopy. Plant canopies can be very open (as in grasslands) or more closed (as in forests). The degree of openness affects the amount of water that is intercepted by the foliage and evaporates back into the atmosphere in the presence of sufficient heat/wind. Forest canopies for example, can intercept between 10%–30% of incident rainfall, reducing local streamflow [100]. The canopies, which intercept the most water and return it to the atmosphere, can have profound effects on local water cycles. In scenarios of high precipitation and during extreme weather events, buildings can be engineered or retrofitted to reduce flood events. Modelling how canopies of different heights and densities intercept rainfall could assist in the positioning of urban greenery (as well as the buildings themselves) in order to increase in the rate of interception, reduce flow rate or increase the amount of water returned to the atmosphere.

Adaptive building envelope technologies are also being developed to mimic the channels produced by plant roots in order to disperse water and slow down flow through the urban environment [101,102]. There are also an increasing range of materials which mimic the way roots and root hairs draw water through the soil and into the plant, transport water passively through the stem, and release water through evaporation. Roots absorb water by utilising negative hydrostatic pressure driven by transpiration to move water from soil to air. In much the same way, materials that wick water are at the centre of new developments to the collection and storage of water upon the building envelope and the controlled irrigation of on-building plants [11,102]. Such materials have the ability to expand to store water, and take advantage of water potential gradients to evenly distribute water for irrigation or to draw water passively to a collection point. The direct application of plants to provide storm water mitigation is a still developing field. Although plants per se have been utilised on roofs, in streets and as barriers to downstream flooding, the characteristics and even species selection for these tasks have yet to be optimised.

4.1. Sustainable Urban Drainage Systems (SuDs)—Building Coverings

The collective term for solutions to storm water is sustainable urban drainage systems (SuDs). SuDs are often fitted in areas with a high degree of impermeable surfaces in order to control large amounts of precipitation during intense storms. SuDs are realised through the application of natural ecosystems such as wetlands, rain gardens and green roofs as well as through engineered solutions such as storage vessels and permeable pavements. SuDs can also be examples of biomimetic design whereby neighbourhoods are designed to take advantage of the way that nature deals with heavy rainfall by increasing infiltration and percolation as well as returning water to the atmosphere via evaporative transpiration. Most forms of urban greenery are sold as contributory to SuDs and come associated with the benefit of reducing storm water run-off. Indeed, the UK code of practice for green roofs highlights this as a benefit of green roofs, mentioning only the change in substrate depth as a factor in run-off reduction [103]. However, it is not clear how many of the green roofs, façades and street plantings that have been installed actually deliver in terms of improving drainage, intercepting rainfall or indeed preventing pluvial flooding, or what the contribution of the installed plants is to this. In other words there is limited monitoring of the benefits of installed schemes, for example to determine the effect of a semi-permeable surface on which plants are growing and the effect of evaporation and transpiration from the plants.

Green roofs are an example of urban greenery designed to directly utilise plants to manage storm water runoff [104]. The hydrological performance of green roofs has been relatively well studied, since water management is perhaps the most marketed benefit of a green roof. Storm water retention is reported to range from 25%–85% for green roofs based on a variety of combinations of substrate and vegetation [105–109] with a median of 50%. As rainfall intensity increases, this effect is also reduced. Although the substrate [110] and drainage layers of green roofs as well as the slope of the roof [111] contribute most significantly to storm water management, the composition of the vegetation is also important [106,112]. In an extensive green roof, vegetation can alter storm water retention by as much as 82% compared with the substrate that the green roof is grown on alone [113]. Prairie grasses have been shown to be twice as effective at reducing run-off as sedum species at the same depth of substrate [106]. In general, the more intensive (deeper substrate) and more species diversity, the more capacity a green roof has to retain, absorb and transpire water [88,112,114]. However, more intensive roofs are difficult to install and often need to be designed in to projects rather than being an option for retrofit. The most recognisable type of extensive roof is the sedum mat (pre-grown mats akin to turf rolls) that can be very simply installed. The ability of such systems to deliver storm water mitigation is likely to be limited. Sedums in particular require very rapid drainage and are most suitable for drought conditions. Systems designed to contain them must therefore allow water to drain away quickly, reducing their effectiveness as a method of storm water run-off mitigation on flat roofs. There is a challenge to discover alternative systems to the sedum mat, which can be produced at a similar price point and ease of installation, but with improved hydrological performance. The mimicry of natural ecosystems is also likely to make extensive green roofs more effective for water management [88]. The investigation of resilient grassland ecosystems may yield alternative mixes of plants which could be established under similarly harsh conditions whilst delivering greater storm water management. Grassland communities might be advantageous when compared to widely used Sedum mats in an extensive green roof system since they have a greater requirement for water and bind the substrate through greater root growth, potentially allowing them to retain and transpire more water than sedum species on a shallow substrate. Grassland communities, particularly those which colonise infertile soils are also biodiverse, adapted to changeable environmental conditions [115], less sensitive to climate change [116], typically evergreen, easy to grow and cost effective. Grass species have naturally colonised old extensive green roofs in Germany, showing that the long-term conditions are favourable for these species [117]. Moss species are also of interest as they are able to retain a large amount of water, survive under extended periods of harsh weather, and naturally colonise existing green roofs [117].

A variation known as the green cloak utilises the dense canopy of vine plants to provide a more effective direct interception of rain water than traditional extensive green roofs [118]. It is possible to imagine systems where vine plants could contribute significantly as a retrofit option for green roofs. With a wire frame and planters placed above the strongest portions of the roof, plants such as ivy (*Hedera helix*), Virginia creeper (*Parthenocissus quinquefolia*), clematis (*Clematis vitalba*) and honeysuckle (*Lonicera penclymenum*) could grow horizontally across a roof space, forming a dense and effective canopy over time. Work in Maryland, US has shown that vine canopies can be effective in slowing storm water run-off and provide effective shading to elements below [118,119]. Several varieties establish within a single season, faster than most green roof mixes [119]. The replication of this work under a variety of climatic conditions and using a wide range of species, together with comparisons with other green roof solutions is warranted to fully elucidate the potential of vines as a lightweight, retrofit SuDs solution.

4.2. SuDs—Ground Coverings

At the street level, a large proportion of green surfaces in towns and cities are grass. Grass has the benefit of providing a robust surface for recreation, which no other type of greenery can. The well-being benefits of green spaces in urban environments are well documented and open parks are a magnet for city dwellers [120]. Open parks are therefore often protected and prioritised in urban planning. These grass covered parks are a consistent and highly preserved feature of urban landscapes and represent a large area of permeable ground which can contribute significantly to the drainage of water during storm events, and also via their topographical design, as temporary detention basins. The traits of the grass species that are used for these areas are of critical importance. Parks are well used. The ground, therefore, can be highly compacted and the grasses themselves rigorously maintained, which could limit their performance against flood water. The belowground growth of these grasses is therefore an important characteristic that contributes to their potential ability to alleviate flooding and offer protection from soil erosion and compaction. Grasses with deep roots create channels in the soil as their roots develop, die and are replaced. They are also more resilient to periods of drought, since the longer roots are better able to reach stores of water in deeper layers of soil. This may also make them more resilient to consistent mowing and wear. Some hybrid grass cultivars have been shown to rapidly develop deep root systems, which then senesce, improving soil structure and drainage to combat flooding on farmland [121]. A new project involving Aberystwyth University is developing hybrid *Festulolium* cultivars (a cross between perennial ryegrasses—*Lolium perenne* sp. and meadow fescue—*Festuca pratensis*) as "climate smart grasses" by investigating their responses to multiple abiotic stressors, including both drought and flooding. The hybrid grass in this study reduced run-off by 51% compared to *L. perenne* and by 43% compared to *F. pratensis* [121]. Novel, deep rooting grasses could be a simple and cost effective contributor to a wider SuDs schema.

5. What Role Can Plants Play in Managing Greenhouse Gas Emissions in Urban Areas?

5.1. CO_2 and Global Warming

The impact of climate change and extreme weather events is predicted to create challenges for those living in cities, including as a result of the urban heat island effect. Despite per capita emissions being lower in cities than in other areas [122], their sheer size and expected growth make them worthy of academic attention. City living create efficiencies of scale which effectively reduce GHG emissions per capita [123] but they still have significant carbon footprints. They are potentially highly cost effective centres for global warming mitigation strategies. Given their ability to fix carbon dioxide, plants are recognised as a CO_2 mitigation strategy even in urban areas. Street trees and parks are common features of cities, fixing carbon and contributing to the health and wellbeing of citizens through aesthetic improvement and air quality enhancement. According to measurements of glacial air bubbles, plants have not evolved in a world where CO_2 concentrations are as high as they are today (~400 ppm), or predicted to be by the end of the century (700 ppm) [124], with CO_2 concentrations not having been so high for more than 26 million years [125]. Certain species appear to be less sensitive to changes in CO_2 concentration such as conifers (Pinophyta) and Beech (*Fagus* sp.) [126]. The adaptations that allow them to remain insensitive to CO_2 changes are of interest. The effects of changing climate on the growth of plants has significant potential for impact in an elevated CO_2 world, and experiments to predict this are being done in the field using an approach known as FACE (free-air carbon dioxide enrichment) [127] although there are questions of scale and a geographical bias towards temperate biomes [128]. FACE experiments involve artificially elevating open air CO_2 concentrations around experimental plots of plants or trees.

Cities could be considered as large FACE experiments due to "CO_2 domes", the clouds of CO_2 enriched air which hover above cities. Research indicates that CO_2 concentrations in cities can be considerably higher than those in the surrounding suburbs and countryside. For example, Widory and Jovoy [129] reported CO_2 concentrations in the centre of Paris reaching as high as 950 ppm compared to an average of 415 ppm in the surrounding countryside. Despite some differences in research methodology, other investigations have revealed consistently higher than average values (10%–40%) in the centres of Rome [130], Copenhagen [131], Tokyo [132], Phoenix [133], Kuwait City [134], Mexico City [135], and Krakow [136]. There, is therefore, an opportunity to study the differences between plants of the same species in a city, outside it, and potentially with those grown in FACE experiments. Cities also provide the opportunity to study the interactive effects of elevated CO_2 together with higher temperatures, drought and higher concentrations of pollutants such as ozone. These stresses interact and vary between plants with either C3 or C4 metabolic pathways [137]. Planners and urban landscapers therefore need to be informed when they make decisions about what to plant in green spaces.

5.2. Carbon Fixation in Urban Areas

Carbon sequestration is viewed as a major contributor to the abatement of global climate change [138]. However, the value of urban ecosystems to carbon balance is often questioned in terms of its relative contribution to global carbon stores. The most convincing counter argument is the expansion of urban areas during the last century. The land covered by "urban" areas is predicted to increase by 1.2 million square kilometres by 2030, representing a tripling of urban land cover since the year 2000 [139]. Meanwhile, it is estimated that a 50% reduction in atmospheric CO_2 emissions is required to limit global temperature rise to between 2–2.4 °C [140]. The retention of greenery in urban areas, and the contributions they make to carbon balance is therefore positive. In a recent study of urban carbon storage encompassing soil and vegetation stores, Edmondson et al. [141] showed that urban carbon storage in a typical city (Leicester, UK) was 17.6 kg·m^{-2}, with 18% being held by vegetation. Edmondson and colleagues concluded that the contribution of urban areas to carbon storage has been significantly underestimated. A recent review evaluating research conducted on urban trees concluded that 27/30 studies, in which CO_2 fixation was measured, were able to demonstrate positive results [142]. The precise contribution of urban trees to carbon fixation varies depending on distribution, tree size and species. In Canberra, the planting of 400,000 urban trees has been estimated to sequester 30,200 tonnes of CO_2 (0.075 tonnes per tree) with an approximate economic value of more than US$20 million between 2008–2012 [143]. Further studies have determined the carbon storage value (or potential value) of trees in urban areas (Table 2). Davies and colleagues [144] noted that there were no standardised methods to accurately quantify the contribution of urban carbon stocks, and that direct extrapolation of carbon values from field based studies has the potential to underestimate the urban values by as much as 76%. The use of high resolution mapping, including applications based around Google's map portal, such as iTree, are increasingly being utilised to quantify and categorise urban vegetation [145,146].

Table 2. Carbon storage (or potential carbon storage) by trees in selected world cities. Based on the number of trees assessed in each study.

Study	City	Total Carbon Storage by Trees (tC)	Carbon Storage per Tree (tC)	Number of Trees Assessed (×10^3)
Escobedo et al. [147]	Miami-Dade, USA	1,497,676	0.041	36,697
Liu and Li [148]	Shenyang, CHN	337,000	0.058	5760
Brack (2002) [143]	Canberra, AUS	30,200 (potential)	0.075 (predicted)	400
Nowak and Crane [150]	New York, USA	1,225,200	0.24	5212
Yang et al. [151]	Beijing, CHN	200,000	0.083	2400
Davies et al. [152]	Leicester, UK	225,217	0.15	1489.244
Stoffberg et al. [153]	Tshwane, RSA	54,630 (potential)	0.47 (predicted after 30 years)	115.2
Strohback and Haase, [154]	Leipzig, GER	316,000	Not assessed. 11.8 per ha	Not assessed
Chaparro and Tarradas, [155]	Barcelona, SPN	113,437	0.080	1419.823

However, there are significant challenges associated with the use of some of these technologies. It is inappropriate to use a generic data type such as "canopy cover" since there is significant heterogeneity amongst vegetation [156]. For example, it has been shown that trees present in domestic gardens are significantly smaller than those in parks or streets. Conversely, this heterogeneity must be balanced against the need to create a small number of distinct categories in order that city wide assessments can be standardised. The study of the contribution of urban vegetation to carbon storage potential, and the development of a set of measureable criteria through which the contribution of different types and sizes of trees and other woody vegetation can be measured is worthy of greater academic attention, particularly in the case of small trees. The size of a tree is determined as a function of stems per unit area and diameter at breast height (DBH). Small trees are often under sampled in city wide assessments despite the fact that they dominate urban settings. This may partly be due to the allometric equations used to estimate biomass being based on forest trees, whilst no specific equations existing for urban or ornamental trees. The result being that true aboveground carbon storage in cities remains relatively undocumented.

The carbon cycle is difficult to measure in urban areas, principally due to the phenomenon of maintenance. In most ecosystems, carbon balance can be determined over the lifetime of the plants. In the built environment, green spaces are heavily maintained through processes such as trimming, mowing, pollarding. There is also a need for low-maintenance constructed ecosystems such as diverse green roofs and façades. A key challenge is to combine data sets between empirical measurements of carbon storage in city species with advanced technological assessments of vegetative cover such as LiDAR. LiDAR (an acronym of Light Detection and Ranging) measures distance by quantifying the refection of light from surfaces, allowing characterisation of the reflecting surface. Air and ground based LiDAR assessments are being developed as way to build up more accurate models of urban surfaces and thus the individual components in urban planning. This technology is currently being used to determine urban vegetation cover [157–159].

Another, often over looked potential for carbon capture and storage in cities is in the fabric of buildings themselves. The substitution of bio-based materials in the full range of applications within a building will undoubtedly lock up carbon for an amount of time. However, whilst this seems intuitive, life cycle assessment and carbon accounting can show otherwise [160,161]. Whether the use of bio-based materials can be seen as an improvement of the environmental profile of a city will depend on the way that it is accounted for, predicted service life, actual service life, maintenance schedules and the end of service life opportunities [162]. The change in the net CO_2 emissions from a city due to the substitution of construction materials will depend on the magnitude of the substitution and the interactions of a number of variables [163]. However Gustavsson and Sathre [164] varied a number of parameters representing the process of production and construction with both concrete and wood and found that wood construction consistently uses less energy and emits less CO_2 than the use of concrete materials.

5.3. Conversion of CO_2 to Energy

The conversion of CO_2 to energy substrates in the presence of light is also a source of inspiration for materials and processes that aim to make use of excess CO_2 and recycle it. Carbon, in the form of CO_2 can be recombined with H_2O to form hydrocarbons which are the basis of modern fuels. Unfortunately, the process has thus far been too energy intensive to become commercially or environmentally viable. Plants utilise energy from sunlight to assemble hydrocarbons and this is the inspiration for a range of new business and research projects which aim to use concentrated solar energy to power their reactions. Technologies to re-capture CO_2 make most sense when they occur close to source. Artificial "trees" are another innovation inspired by the natural process of photosynthesis, where function rather than form is replicated. These "trees" are actually large towers containing sorbents which absorb CO_2 at rates which potentially exceed the capacity of natural vegetation by up to 1000 fold [165]. The process requires energy, but can potentially also be combined with renewable energy technologies. Such trees are made up of artificial leaves made from resins which contain chemicals similar to those used to soften water. Captured CO_2 could also be piped into urban greenhouses or reactors containing micro algae [166].

6. Conclusions

This review has argued that there are opportunities for a greater integration of plant science in building disciplines to stimulate further innovation in urban design and planning. In each section, current research and opportunities were discussed from the perspective of an over-arching question concerning the management of key environmental parameters in urban environments. In order to summarise the discussions and research herein, we are, in this conclusion, identifying important areas for each environmental parameter (light, heat, water, and CO_2) where plant research has enhanced the adaptation of the built environment to environmental parameters, or where there is a need for further research to develop the impact of plant science on urban design and planning.

Light:

1. Further develop passive, adaptable smart surface (glass/panels) technologies based on the ability of plants to selectively absorb, focus, avoid, or scatter light.
2. Learn from leaf angle and orientation to design fenestration to optimise light distribution in internal spaces throughout the day
3. Adopt a co-modelling approach between urban modelling and functional structural plant modelling to map functional relationships between urban components in terms of light use.

Heat:

1. Identify the balance between solar heat gain and shading to manage the internal environment through building envelope greening in both summer and winter across a variety of climates.
2. Understand the contributions of different elements of constructed ecosystems like green roofs (species, microbial interactions, nutrient cycling) to their ability to maintain vegetative coverage.
3. Quantify the contribution of plant parameters, particularly leaf area index, vertical canopy thickness, and total canopy coverage to the thermal properties of green infrastructure in the urban environment.

Water:

1. Develop a better understanding of the vegetative structures that result in the most effective interception and evapotranspiration of water in urban landscapes.
2. Further innovation in the collection and storage of water on buildings, either within vegetated systems, for use by them, or to slow down storm water run-off.
3. Optimise plant species for SuDs schema, including permeable grassed surfaces and specifically designed drainage areas, and the effective contribution of different green infrastructure elements under different storm water scenarios for urban water planning.

CO_2:

1. Better understand how plants are affected by elevated CO_2 (present in urban environments) through the study of naturally insensitive species such as pine and beech, in response to climate change projections.
2. Develop more standardised methods for valuing the contribution of urban trees and plants to carbon stocks, and their fluctuations, to design low maintenance spaces to maximise carbon fixation and storage. Couple empirical measurement with technology (i.e., LIDAR).
3. Further develop biomaterials for the capture and storage of carbon in building structures.

The research reviewed here shows that plants can play a considerable role in the adaptation of the urban environment to environmental stresses. Where plants are used directly, it is vital to understand the links between plant traits and the ecosystem service intended. Plant selection can have a large bearing on functionality, and we need more knowledge on the matching of plants to different urban scenarios. To achieve that aim, we must further understand the impacts of urban environments on plants, particularly in green infrastructure solutions. Furthermore, there is still a dearth of information on the long-term viability and functionality of green infrastructure, and a concerted effort is required to provide post-installation monitoring data for such sites to inform future planning and to develop more practical options for retrofitting buildings with green infrastructures. Owing to the limitations of traditional building design and the added cost associated with green solutions, many are cost engineered out of new build or refurbishment projects. It is therefore necessary to demonstrate green solutions that can provide both aesthetic impact and long-term performance in both retrofit and new design scenarios. Plants have been the source of a number of biomimetic solutions for adaptive building design, and further interaction between plant scientists and researchers in the built environment can continue to drive innovation, and bring new creative solutions to environmental challenges. A move away from the mimicry of form, towards the mimicry of function and its underlying mechanism is a trend in biomimetic research, and one that can provide a significant opportunity for interaction between biological scientists and urban infrastructure planners/creators. Biological control mechanisms, organism/community symbioses, and adaptive responses are all elements of plant science that can offer new opportunities for biomimicry in urban spaces. These are the interactions that have great potential to provide the inspiration for smart and responsive technologies that could allow cities to mimic the environmental plasticity that make plants so successful.

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