Chapter 2
Perspectives on Greening of Cities Through an Ecological Lens

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Abstract The increasing focus on urban green spaces (UGS) leads to them becoming an important component of the physical makeup of cities. However, it is useful to be mindful that UGS implementation competes for precious land resources in cities, incur carbon and energy footprint, and can have long payback periods for net benefits to be achieved. The net benefits provided by UGS are thus not assured by its mere presence; functional benefits need to be achieved through deliberate design. In particular, it is suggested here that combining design with an understanding of urban ecological knowledge is a useful approach to increase the ecological functions of UGS. A conceptual model using coupled human-ecological function is described to explain how increasing ecological functions of UGS to reduce resource consumption, restore ecological processes and functions, and reduce waste generation can shift the coupled human-ecological function for both humans and the environment. Four principles distilled from conceptual advances in urban ecology and landscape ecology are proposed as a means to bridge scientific knowledge and UGS implementation through design: (1) spatial patterns of UGS across different scales influence the ecological functions of UGS; (2) heterogeneity of UGS determines its resilience to disturbances; (3) urban ecosystems are dynamic; and (4) ecological processes remain important in cities. More application-focused strategies are in turn, derived from these principles, and how these can be applied to UGS are highlighted. It is also suggested that while current scientific knowledge still limits the application of ecological principles in many aspects of UGS design and management, the increasing emphasis on UGS in cities provides good learning opportunities for scientists, practitioners and policy makers to work in concert to enhance the ecological functions of UGS.

Keywords Urban greening · Urban ecology · Ecological function · Ecological design · Ecological principles · Coupled human-ecological function

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P.Y. Tan and C.Y. Jim (eds.), *Greening Cities: Forms and Functions*,
Advances in 21st Century Human Settlements,
DOI 10.1007/978-981-10-4113-6_2

2.1 From Being Green to Becoming Ecological

The effort of cities to introduce more urban green spaces (UGS) can be seen in numerous strategic and sustainable development initiatives of cities worldwide. Such a focus on greening cities can also be observed in the physical increases in green spaces within cities over the past few decades. For instance, Zhao et al. (2013) reported that more than 90% of 286 Chinese cities in their study increased in average green space coverage from 17 to 27% between 1989 and 2009. The authors suggested that this could in part, be attributed to the increasing economic wealth experienced in many cities over this period. Kabisch and Haase (2013) in their assessment of 202 European cities also reported that in Western and Central Europe, there was a marked increase in urban green spaces between 2000 and 2006. In these European cities, urban green spaces[1] occupy almost 15–30% of the city area, depending on urban data set used. Between 1991 and 2006, 12 out of 13 cities in England in the study of Dallimer et al. (2011) also had increased green spaces, with green space occupying an average of 24% of the city area. In the American rust belt, shrinking cities also experience increasing number of vacant lots, some of which have become woodlands due to spontaneous regrowth, and others are proposed to be incorporated into green network in the cities (Burkholder 2012; Frazier and Bagchi-Sen 2015). These studies demonstrated two key points: that green spaces respond to urban policies (such as densification, open space provision, and brownfield development) and economic forces, and are hence dynamic. In addition, as shown over a large sample of cities, UGS can occupy as much as 30% of the city area.

Especially in the context of dense, high-population densities with land constraints, land occupied by such green spaces are not insignificant compared to other land uses. In Singapore, for example, total amount of green spaces dedicated to parks, nature reserves, street planting verges, rooftop greenery, and interstitial green spaces between buildings in residential estates and commercial land together occupy about 30% of land in Singapore. This is more than twice the amount of planned residential land which houses 83% of the total population (about 4.6 million), and two and half times the amount of land set aside for industry and commerce.[2] In Hong Kong, land for open space which includes park and garden, playfield, pavilion, etc. constitutes about 60%[3] of total land area set aside for residential use, which houses about 7 million people.

The comparison of land uses pointed out here is not to suggest that land set aside for urban green spaces is disproportionately higher or wasteful compared to other

[1]Note that ‘urban green space’ in this study was defined as green spaces ≥ 25 ha, i.e., excluding green open spaces between buildings, sports and recreational facilities.

[2]Data from Concept Plan Review 2000 and Tan et al. (2013). Urban green spaces considered exclude green field sites zone for other land uses.

[3]Source of information: Land Use Utilization (2014) from Planning Department, Hong Kong Special Administrative Region.

land uses, nor to suggest that urban green spaces should always have an instrumental value. Rather, it is to highlight that uptake of UGS is not insignificant compared to other land uses, and therefore, what are the benefits that can be derived from the land dedicated for UGS is a responsible question to be asked by urban planners and designers. After all, all UGS, regardless of forms and scale, consumes resources for construction and maintenance, i.e., there is a carbon and energy footprint associated with their provision. It is also necessary too to consider that urban greenery implementations as shown in life cycle assessment, can have long payback periods of 20–30 years even under optimally designed conditions, such as in the case of green walls (Pan and Chu 2016) and water sensitive urban design elements (De Sousa et al. 2012; Flynn and Traver 2013). Other forms of UGS which have not been designed for specific functions could even have longer payback periods. In cities which undergo short real estate redevelopment cycles, urban greenery installations may not even exist long enough for payback period to be reached and net benefits of the installations to be achieved. Yet, it is common to see in cities implementation of UGS that have seemingly failed to consider the costs aspects of installation and maintenance, and large scale installations that have even questionable aesthetics benefits. An example is shown in Fig. 2.1 (see also examples of poorly designed UGS in Jim and Chan 2016). Quigley (2011), in

Fig. 2.1 A towering green wall covering the stairwell of a residential building in Singapore (*left*). However, while ambitious as a design feature, the creepers on trellis can reduce daylight and ventilation in the stairwell, and the green wall is only visible on exterior of the building. The visual attractiveness is questionable, ecological functions are limited, and maintainability of the system is low (*right*) (*Photo credit* P.Y. Tan)

referring to the potential of urban landscapes to function as habitats if appropriately designed, criticised many urban landscapes as 'Potemkin gardens', which are created for 'two-dimensional visual effect', and which lack 'connectivity, function or self-sustainability'. Lim and Lu (2016) also remarked that for the large capital investment that has been put in for the 60 completed water sensitive urban design projects in Singapore for the past decade, efforts should be directed at realizing the hydrological and ecological potential of such projects, as otherwise, many of these are mere 'gardening efforts' around urban infrastructures. These accounts highlight an observation made more than thirty years ago that 'nature has been seen as a superficial embellishment, as a luxury, rather than an essential force which permeates the city' (Spirn 1984: 5).

The key point emphasized here is that due to land uptake, energy and material costs of UGS, making urban areas visually green is useful but inadequate; greening should be a means to deliver more functional benefits for human well-being and environmental quality. One relevant perspective suggested here is that urban greening should become more 'ecological'. What does being more ecological entail and what are the broad strategies that could guide the design and implementation of UGS to achieve this objectives? Given that UGS takes many forms, from city-scale green infrastructure, to community scale neighbourhood green spaces, and to building scale installations of green roofs or green walls, these strategies should also necessarily consider the effects of scale and specificity of sites. Using key concepts of urban ecology and landscape ecology that have shaped our understanding of cities as socio-ecological systems, this chapter describes a conceptual model to frame the notion of greening as a means to increase ecological functions in cities and the key approaches for achieving this aim.

2.2 Greening to Increase Ecological Functions in Cities: A Conceptual Model

Making urban greening more 'ecological' as used here simply denotes deriving more ecological functions from UGS through deliberate design. There are two parts to this statement. The first on ecological functions draws reference to the rapidly expanding literature that UGS is capable of providing ecosystem services, or functional benefits through natural ecological processes (Bolund and Hunhammar 1999; Elmqvist et al. 2015) for urban liveability and resilience. The second relates to the argument that functional benefits of UGS need to be deliberately designed, using the notion of design as 'an intentional change of landscape pattern for the purpose of sustainably providing ecosystem services while recognizably meeting societal needs and respecting societal values' (Nassauer and Opdam 2008). That is to say, benefits of greenery should be targeted rather than incidental. The overarching perspective adopted here is that all over the world, land use and land cover changes during urbanization drastically transform natural ecosystems and ecological processes occurring therein, as well as outside the boundaries of cities (McDonnell and MacGregor-Fors 2016). UGS then, as argued here, is a principal medium to restore natural ecological flows and functions which have not disappeared from urban landscapes, but have simply become highly altered or impaired.

Key examples of such changes are the highly altered flow of water, nutrients, and energy, as well as reduction of habitats for biodiversity that occur during urbanization. The range of ecological processes associated with the disturbances to these ecological functions is listed in Table 2.1. Perhaps one of the most striking ways in which ecological flows have undergone dramatic transformations in the course of urbanization is how humans have manipulated water supply, waste water treatment, stormwater drainage in urban areas, and the appropriation of water resources to support expanding urban demands (Forman 2014: 84). Indeed, in the urban history of urban settlements, such advances in urban water management have served human needs well, and have contributed remarkably to improving sanitary conditions in cities, which is considered as one of the most important medical advances for human health in our urban history (Larsen et al. 2016). However, there is now growing concern that largely because of resource depletion, pollution and climate variations, ensuring a safe and sustainable water supply for large urban regions of the world is increasingly become a global challenge (Padowski and Gorelick 2014; Vörösmarty et al. 2000). Inevitably, water scarcity also begins to threaten food security for large populations in both developed and developing countries (Hanjra and Qureshi 2010). In other words, while humans have through innovations, developed technologies and appropriated natural resources to satisfy our existential needs and well-being, and are seemingly detached from natural ecosystems, in reality, we are still fundamentally dependent on natural resources and ecological processes for our well-being in the long-term. This is well-illustrated in the concept of Daly Triangle (described in (Wu 2013), which essentially suggests that the pursuit of human well-being cannot be achieved without safeguarding natural ecological processes and functions as the earth's life-support systems. The integrity of natural ecosystems, or natural capital, is the ultimate means on which human well-being has to be built upon, whereas technological, economic and other human and societal pursuits that lead to accumulation of built and financial capital can only serve as intermediate means for this purpose.

Another useful conceptual model that illustrates the interdependence of human and ecological functions is the conceptual model proposed by Alberti (2008a). The model highlights the flawed notion of decoupling (and substitutability) between 'human functions' (human inventions, built capital and resource appropriation to satisfy human existential needs and well-being), and ecological functions. Human and ecological functions, as also embedded on the Daly Triangle, are interdependent and mutually reinforcing. As such, beyond a threshold or tipping point, the impairment of ecological functions with continuing urbanization based on a business-as-usual mode will lead to human functions being depressed as well (Fig. 2.2). Alberti further suggested that the state of this coupled human-environmental functions, as determined by urban forms and

Table 2.1 Ecological functions and processes which are influenced by urban landscapes

Socio-ecological functions	Impact of urbanization on ecological processes	Potential of urban green spaces to reduce impacts of urbanization
Ecological functions		
Primary production—*capacity of urban areas to produce photosynthate and accumulate biomass*	? Net primary production ? Carbon storage and sequestration	? Low potential for carbon sequestration (Pataki et al. 2011)
Hydrologic function—*capacity of urban areas to maintain natural hydrological cycle through interception, infiltration, evapotranspiration*	↑ Runoff ↑ Nutrients and pollutants discharge ↑ Erosion/sedimentation ↑ Increased water temperature ↑ Flashiness of runoff	High potential stormwater mitigation (Larsen et al. 2016; Pataki et al. 2011) High potential for water-quality improvement (Land et al. 2016; Larsen et al. 2016; Pataki et al. 2011) ? ? High potential for stormwater mitigation (Larsen et al. 2016; Pataki et al. 2011)
Nutrient cycling—*capacity of urban areas to retain, allow for biological uptake and accumulation, and recycling through decomposition or inorganic processes*	↑ Nutrient runoff and ↓ nutrient uptake ↑ Eutrophication ↑ Soil NO_3 and nitrification ? Trophic interactions ? Ecosystem metabolism	High potential for water-quality improvement (Land et al. 2016; Larsen et al. 2016; Pataki et al. 2011); ? ? ? ?
Habitat provision and biodiversity—*capacity of urban areas to support biodiversity, which is in turn the foundation of other ecological functions*	↓ Habitat diversity ↓ Species diversity ↓ Native species ↑ Tolerant/generalist species ↑ Invasives	Medium potential for habitat provision, as local and regional processes are important, and adequate habitat area is required for successful conservation (Beninde et al. 2015; Faeth et al. 2001; Strohbach et al. 2013)

(continued)

Table 2.1 (continued)

Socio-ecological functions	Impact of urbanization on ecological processes	Potential of urban green spaces to reduce impacts of urbanization
Disturbance regulation—*capacity of urban areas to withstand disturbances such as climate change, weather extremes, invasives, flooding, erosion, insect/pathogen outbreak*	↑ Weather variability ↑ Flooding ↑ Drought ↑ Landslides ↑ Heat stress	? ? ? ? High potential for local cooling (Coutts et al. 2013; Davis et al. 2016; Pataki et al. 2011; Santamouris 2015)

Information presented are mainly extracted from review papers that synthesise current understanding. Ecological processes and urbanization impacts are extracted from (Alberti 2010): ↑↓ indicate direction of changes in functions, and ? indicates uncertainties in current knowledge. Potential of UGS to moderate changes in ecological processes: low, medium and high indicates potential contribution as used in (Pataki et al. 2011)

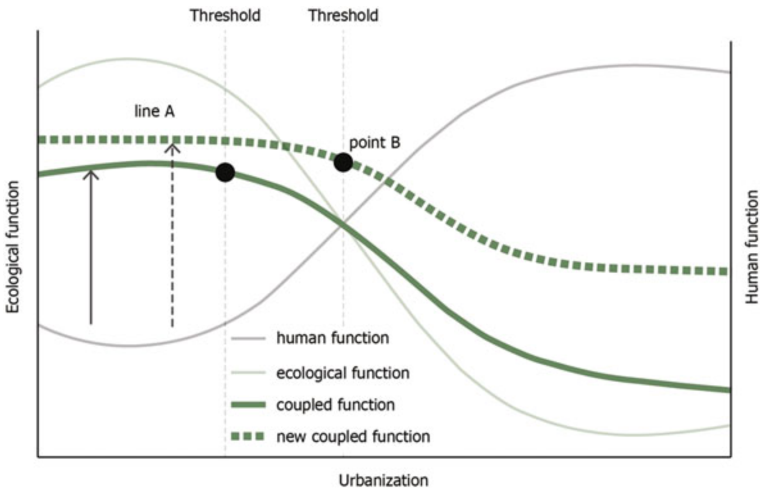

Fig. 2.2 As urbanization increases, ecological functions are reduced due to urbanization impacts on the environment, whereas human functions (built and financial capital, human well-being) increases. In reality, human and ecological functions are coupled and human well-being cannot be sustained beyond a threshold at which ecological functions are degraded. Focusing on ecological functions of UGS can push the coupled function to provide higher ecological and human functions (to *line A*), and extend the threshold of failure of ecological functions to *point B*. Numerous human-ecological functions are theoretically possible. Adapted from Alberti (2008a)

patterns, can also be instrumental in influencing urban resilience to external disturbances such as climate change (Alberti 2008a).

We highlight a role for UGS in this model: it is proposed here that UGS should serve as a medium to enhance ecological functions in cities. Enhancing ecological functions in cities could lead to two possible outcomes in this model. Firstly, UGS implementation can be directed to reduce resource consumption within cities, reduce resource appropriation from cities' hinterlands, restore ecological processes and functions in cities, and reduce waste generation (such as nutrients and pollutants). This reduces the rate of decline in ecological functions with urbanization, within and outside cities, and at the same time, through benefits conferred to urban dwellers, shifts the coupled human-ecological function to a more positive state (line A in Fig. 2.2). These cumulative effects could then increase the threshold beyond which human and ecological functions are impaired and become irreversibly transformed (to point B). In this way, the ability of urban systems to tolerate disturbances or stressors arising from impaired or disrupted ecological functions, a component of urban resilience, can also be enhanced. Viewed in this sense, greening of cities extends its role beyond creating a visually pleasing urban environment; greening should be viewed as an essential means to enhance both human functions and reduce environmental impacts.[4] Specific ways in which the ecological and human functions interact, and influence of socio-economic and environmental factors external to cities' environment would then mean that there will be a range of shapes and positions of line A, and where point B falls in this coupled function.

Is there evidence for such roles of UGS? This can gleaned from an increasing amount of studies on urban ecosystem services provided by UGS, which provide an emerging consensus of the types of ecological functions that are particularly valuable in urban areas. Several key examples are provided in Table 2.1, which summarizes the current evidence that UGS can mitigate changes to ecological processes and functions associated with urbanization. While not all types of ecological functions can be realistically or impactfully restored by UGS, current evidence suggests that localized heat mitigation, stormwater mitigation, stormwater quality improvement, and habitat provision are primary areas which UGC can make contributions to reduce our reliance on energy, conserve and protect water resources, and support biodiversity. Elmqvist et al. (2015) also recently demonstrated that enhancing ecosystem services in urban areas is not just ecologically and socially desirable, but is also an economically viable option. While this chapter only focuses on roles of UGS in enhancing ecological functions, it should also be noted that there is a large body of evidence highlighting that UGS has important roles in the socio-cultural aspects of urban living, particularly for individual and community well-being, social capital and sense of place. Aspects of these functions are discussed in Chaps. 5, 6, 8, and 13.

2.3 From Ecological Knowledge to Action: Approaches to Increase Ecological Functions of UGS

What approaches are useful to increase ecological functions in cities? As highlighted in earlier in this chapter, highly functional UGS requires knowledge to be used in deliberate design in professional practice. This is especially important in the context of an 'action gap' in translating knowledge from science into action in professional practice for the design of the urban environment (Wang et al. 2014; Opdam et al. 2013). Given that UGS is an integral and often sizeable part of physical make-up of cities, and our understanding of cities has been increasingly shaped by the burgeoning field of urban ecology and urban landscape ecology, it is logical to focus the approaches and narrow the action gap based on our understanding from these disciplines. Indeed, there is a growing call to use urban ecological knowledge to improve urban conditions, be it for urban liveability

[4]Understandably, UGS is important as an essential, but not sole means for this purpose. We have also suggested that focus on urban systems need to extend beyond the social and ecological components to be also directed to the built components of cities (buildings, roads and other infrastructures), given that the built components are usually dominant in cities (see Tan and Abdul Hamid 2014).

(McDonnell and MacGregor-Fors 2016), urban sustainability (Wu 2014), or urban resilience (McPhearson et al. 2016). Urban ecology and its allied disciplines are increasingly seen as a holistic foundation for the science of, and basis for pushing knowledge-to-action in urban systems (Childers et al. 2015; McPhearson et al. 2016).

It is also useful to note that urban ecology is in itself, a young and evolving discipline that will need to increasingly incorporate other disciplines, so that new methodologies, approaches, and concepts from other disciplines can be used to address urban challenges (McDonnell 2012). As an evolving discipline, the emphasis of urban ecology has also shifted over the past two decades. This shift has frequently been described as a shift from *ecology in cities* to *ecology of cities*. The former refers to studies on ecological conditions of green areas as analogues of wild or rural ecosystems occurring in urban areas and how organisms and biogeochemical processes are affected by urban conditions. The latter emphasizes cities as hybrid ecosystems with tightly coupled social and ecological components, and in which the understanding of human as an agent of, and the responders to changes occurring within the urban ecosystem is a principal means to manage cities as complex, adaptive ecosystems (Grimm et al. 2000; McPhearson et al. 2016;). More recently, Childers et al. (2015) described the need for urban ecological studies to build an *ecology for cities* emphasis, underscored by the need to use knowledge from urban ecology and its allied disciplines in urban planning, urban design, governance and engineering, etc., for a more action-oriented and transdisciplinary approach to meet urban challenges.

What do all the conceptual developments, and advances in tools and approaches mean for the aim of increasing the ecological functions in cities through UGS? How can gains in our knowledge of urban ecological systems be put to use in the design, implementation and management of UGS? These questions are not new. There has been an on-going effort to link ecological science to design (for example, see Hwang et al. 2016; Johnson and Hill 2002; Lovell and Johnston 2009; Nassauer and Opdam 2008; Pickett and Cadenasso 2008). This chapter draws upon insights from these works for specific application to UGS. In particular, a useful entry point for this effort is the synthesis of ecological principles from our understanding of the nature of cities through an ecosystem perspective. Ecological principles, as used here refer to basic assumptions about urban ecosystems, how they function and how these premises can be used to guide landscape planning and design. Principles are useful as they help to translate our conceptual understanding of complex systems into concise statements for the framing of important issues. Principles are also useful to provide general insights for a developmental pathway towards an ideal or desired condition, and are analogous to a compass for direction finding under different circumstances (Luederitz et al. 2013).

Various scholars have synthesized ecological principles that can be applied to the design of the urban environment. For instance, Flores et al. (1998) proposed five principles based on ‘content’, ‘context’, ‘dynamics’, ‘heterogeneity’ and ‘hierarchies’ for the management of green spaces of the New York City Metropolitan Area. Dale et al. (2000) under the Ecological Society of America’s Committee on

Land Use proposed ecological principles based on themes of ‘time’, ‘species’, ‘place’, ‘disturbance’ and ‘landscape’ and through these, recommended guidelines as ‘practical rules of thumb’ for making decisions on land uses. Zipperer et al. (2000) compared the ecological principles of Flores et al. (1998) and Dale et al. (2000) and added the principle concerning ‘connectivity’ to highlight the need for functional connection between green patches, corridor and the landscape matrix in urbanizing landscapes. Subsequent efforts by Cadenasso and Pickett (2008), Wu (2008) and Pickett and Cadenasso (2013) added new perspectives on effects of urban forms and patterns, interacting social and ecological processes, and the role of urban design for experimentation.

Unfortunately, it is also clear from our review of the literature that confirmed generalizations on functioning of urban ecological systems are scant, as highlighted by McDonnell and Hahs (2013). In particular, specific rules based on ecological principles for direct application in design are also rare. Nevertheless, it is suggested here that principles provide ‘the best bet’ for linking science with design. The following section builds upon the earlier syntheses by other scholars, and translate the understanding of these principles into strategies focused on the design, implementation and management of UGS to enhance their ecological functions.

2.4 Ecological Principles and Strategies for UGS

This section describes the principles, applicable strategies and implications for UGS implementation and management. It is acknowledged here too that there needs to be a continuing effort to keep pace with the increasing knowledge from science and translate these into practice through other specific strategies and tactics. Table 2.2 lists the four principles and eight strategies focused on UGS.

Table 2.2 Principles and strategies for UGS implementation to enhance ecological functions

Principles	Strategies
Spatial patterns of UGS across different scales influence the ecological functions of UGS	(a) At the city or regional scale, conceive and implement a network of UGS that that can guide the development and management of UGS in the long-term (b) Consider scale in association with landscape pattern for UGS implementation
Heterogeneity of UGS determines its resilience to disturbances	(a) Maintain a diversity of UGS forms in cities to enhance landscape heterogeneity (b) Increase species diversity and functional diversity in UGS
Urban ecosystems are dynamic	(a) Design UGS to accommodate, not resist, changes brought about by natural growth processes
Ecological processes remain important in cities	(a) Design UGS to restore ecological flows (b) Layer ecological functions to achieve multi-functionality in UGS (c) Integrate ecological functions with built infrastructures

2.4.1 Principle 1—Spatial Patterns of UGS Across Different Scales Influence the Ecological Functions of UGS

This first principle relates to a key tenet of landscape ecology, that landscape patterns (configuration and composition) affect landscape processes and functions (Turner 1989). The distribution, size and shape of green patches govern the interactions between patches in the form of flow of materials and energy flow between UGS, and between UGS and its surrounding matrix. Alberti (2005) further extended this understanding to urban ecosystems, and cogently illustrated the evidence on the influence of urban patterns on urban hydrology, primary productivity, biodiversity, nutrient and materials cycle, etc. For instance, the pattern of UGS, both in terms of shape of individual green patches of UGS (e.g. edge to interior ratio), and extent of physical and functional proximity (e.g. connection of green patches by riparian corridors) can influence the ability of green patches to support biodiversity (Flores et al. 1998; Dramstad et al. 1996). Recent studies on cooling ability of UGS are also beginning to reveal the influence of distribution and configuration of UGS as cool islands (Kong et al. 2014; Chen et al. 2014). UGS patches have been shown to confer different levels of cooling depending on the shape, size, density of patches and vegetation composition of the green area. Patterns of UGS thus influence ecological functions. Unfortunately, the state of scientific knowledge does not allow confirmed generalizations to be drawn on cooling, and other operational relationships between patterns and a range of ecological functions important in urban areas. For instance, we still do not know from the limited literature, if a single large green space, or several small distributed green spaces are more effective for urban cooling, and how this relationship is influenced by built forms and climatic conditions of cities. There is nevertheless a range of guidelines developed from first principles, such as those synthesized by Dramstad et al. (1996) that could be also be tested in urban landscapes. The pattern-process-function principle also dictates that scale is important and that it is therefore desirable to have a multi-scaled view of UGS, from an overarching view at city scale, to regional and local considerations of patterns of UGS. Two strategies are suggested for application of this principle:

(a) At the city or regional scale, conceive and implement a network of UGS that that can guide the development and management of UGS in the long-term.
    Such a UGS network should emphasize functional connectivity between UGS patches, and not just focus on structural or physical connectivity. Functional connectivity refers to the level of spatial connectedness which allow for realized movement of organisms (Auffret et al. 2015). The underlying premise is that a functionally connected network of UGS is likely to support more ecological functions and tolerate disturbances than highly fragmented patches. For

the support of biodiversity for instance, Abdul Hamid and Tan described in Chap. 12, a city-scale ecological network for biodiversity conservation in Singapore that takes into account current distribution and state of fragmentation of green spaces, habitat quality, and species dispersal requirements. The value of such a network is that it highlights parts of the network that are valuable for conservation, parts that are threatened with future developments and hence requiring specific landscape and urban design interventions, and parts which are currently isolated but which could be connected by greening of the urban matrix or restoration of degraded sites. A network identified at this scale thus provides a long-term guide for current and future land developments. On top of biodiversity enhancement, such a network can also be functionally differentiated with overlays of other uses such as recreation and urban hydrological management. This overview provides valuable information at a coarse scale that can guide other future urban developments.

(b) Consider effects of scale on ecological functions for UGS implementation.
The design of UGS to deliver enhanced ecological functions has to consider the relationships between scale of implementation and ecological processes driving those functions, as the relationship between pattern and process is scale dependent (Wu 2008). For instance, while the role of UGS in mitigating the Urban Heat Island effect is well-recognized, the overall benefits are highly dependent on relative amount of vegetated surfaces that confer cooling benefits, and built surfaces that retain and re-radiate heat. This relationship changes with scale. While a large tree next to a low-rise building may provide cooling benefits through shading or evaporative cooling at this microscale level, this benefit is reduced when the tree, or a row of trees are placed within a large development area with high-rise and high-density building towers. At the mesoscale, it should be expected that the effects of anthropogenic heat sources, wind-patterns and other aspects of regional climate also become important in the overall heat balance. In the area of blue-green infrastructure management (Chap. 10), scale considerations are particularly important. In Singapore, there are numerous installations of bioretention systems or rain gardens implemented as part of national efforts improve stormwater quality and reduce flood risk through water sensitive urban design. However, many of such UGS are installed over small areas within a development, in which treated stormwater in one sector is subsequently mixed with upstream, or downstream untreated stormwater collected in conventional drainage systems, leading to questionable overall net benefit of stormwater management (Fig. 2.3). Such installations fail to consider that urban stormwater management has to be tackled at watershed scale (Walsh et al. 2016), and not at the scale of a small green space or planted verge along a street. Designing without understanding scale effects on ecological functions can lead to counterproductive and wasteful use of resources.

Fig. 2.3 A rain garden designed to treat stormwater runoff from the service road of a residential estate in Singapore (marked in *white lines*). Note however that the treatment is highly localized; and runoff from upstream and downstream in the same road, as well as runoff from other paved areas in this precinct are not treated. Overall net benefits for stormwater management at the precinct scale can be questioned

2.4.2 Principle 2—Heterogeneity of UGS Determines Its Resilience to Disturbances

Landscape heterogeneity is the spatial patchiness of landscape patterns, both in configuration and composition of UGS patches. The influence of landscape heterogeneity on a range of ecosystem functions in natural ecosystems is well known. Landscape heterogeneity for instance, influences species presence and abundance, species composition, biotic and abiotic interactions, etc. (Chapin et al. 2011; Turner et al. 2013). A principal influence of heterogeneity highlighted by Flores et al. (1998) is that heterogeneity of green spaces helps to maintain greater species diversity, which is in turn a key feature that enables continued functioning of ecosystem during environmental changes. This strategy should also guide the planning and management of UGS.

(a) Maintain a diversity of UGS forms in cities to enhance landscape heterogeneity. UGS in cities can exist in different forms, from managed spaces such as parks, street planting verge, rooftop greenery, green walls, to natural or unmanaged spaces such as nature reserves, remnant primary and secondary forested areas, young regrowth woodlands, scrublands, etc. In relatively young and still urbanizing cities such as Singapore and Melbourne, continuing land developments on remnant native vegetation will slowly tilt the composition of UGS in the city to be dominated by managed forms of landscapes over unmanaged forms of landscapes (Tan, 2016: 190). This change in landscape type has implications which are often not recognized: for instance, the ability of urban landscapes to support biodiversity is reduced, as remnant native vegetation is critical to support urban biodiversity (Chong et al. 2014) and the extent of its conservation is known to be strong predictor of extinction rate of extant species of cities (Hahs et al. 2009). As Tan et al. (2016) also argued, there are also a range of ecological and socio-cultural values that are lost when secondary forests are developed as such values are often ignored in land use planning. As cities lose more of its native vegetation, and more managed forms of UGS appear in urban areas, there is a risk that UGS become dominated by urban landscapes of similar forms and similar floristic composition (Qian et al. 2016), leading to an emergence of 'landscape homogenization' with continued urbanization. Landscape homogenization, in limiting the ability of UGS to act as habitats for a wide range of biodiversity could then be a factor among other urban drivers that lead to the phenomenon of biotic homogenization, which show up through large similarities in species composition observed in cities (McKinney 2006). The strategy of enhancing urban landscape heterogeneity encourages conservation of valuable remnant native vegetation, which can be incorporated into a city or regional scale network of UGS described earlier, and also calls for increasing structural diversity of vegetation in the design of UGS (see also Chap. 7), and increasing plant diversity (point below).

(b) Increase species diversity and functional diversity in UGS
High species diversity is an insurance against changing environmental conditions (Alberti 2008b; Flores et al. 1998) and should be encouraged in UGS implementation. It has also been highlighted recently that increasing functional diversity, which is the diversity of plant functional traits, rather than species richness of plants alone, is key for increasing ecological functions (Beck 2013: 118). Plant selection for UGS should thus focus on enhancing species diversity and functional traits in aspects such as plant habit, height, leaf area, physiology and resource needs, etc.

One example of increasing landscape heterogeneity in urban areas is the use of tiered and cluster planting of street verges with high species variety, in contrast with conventional monoculture planting of trees at uniform spacing (Fig. 2.4). Another example is to recognise the value of spontaneous vegetation (Fig. 2.5) and urban woodlands (Chap. 13), and allow for their establishment in the built environment. These should have a recognized role in enhancing landscape heterogeneity, as well

Fig. 2.4 An example of cluster planting along a roadside planting verge in Singapore, with tree canopy, shrubbery and ground cover. Such a type of cluster planting creates a new aesthetics for streetscape, and provides refuge for small animals, and with the right plants, supports biodiversity (*Photo credit* P.Y. Tan)

Fig. 2.5 Contrast between the conventional turfed areas under trees on the *left*, and spontaneously generated area on the *right* when mowing was stopped in a landscaped area in Singapore. In addition to creating visual interest, the patch on the right supports a much higher level of biodiversity (*Photo credit* P.Y. Tan)

as for their role to provide a range of ecological functions (Robinson and Lundholm 2012).

2.4.3 Principle 3—Urban Ecosystems Are Dynamic

Natural ecosystems are constantly responding and adjusting to past and current changes in environmental conditions (Chapin et al. 2011). In urban ecosystems, in addition to environmental factors, social factors act as additional drivers that make urban ecosystems highly dynamic (Flores et al. 1998). For instance, the extent of UGS in a city, as highlighted earlier in the chapter, respond to policy changes. The composition of UGS, for instance, the vegetation in a park, also undergo natural successional processes, are subjected to environmental stresses of drought and temperature changes, and are influenced by societal factors such as level and quality of horticulture care and aesthetic preferences. The dynamism experienced simply reflect the basic fact that ecological processes continue to take place in managed urban ecosystems (see Principle 4), and UGS should be designed to work with, not against changes.

(a) Design UGS to accommodate, not resist, changes brought about by natural growth processes.
It is common in urban areas to see urban vegetation implemented that requires high level of maintenance. Extreme examples are lawns and playing fields that require high level of irrigation and fertilization to maintain them in conditions acceptable for their purpose. In such examples, the energy and carbon costs associated with maintenance operations are accepted as societal or economic decisions in return for the utilitarian values provided, such as for recreation. There are however, also many instances of UGS implementation in which maintenance is high but both utilitarian and ecological functions are low as a consequence of failure to accommodate the growing needs of plants. An example is the prevalent use of shrubbery on highly restricted spaces in roadsides that subsequently require regular pruning to prevent traffic obstruction, and yet which do not serve apparent ecological functions (Fig. 2.6). Another prevalent example is the creation of 'instant landscapes', in which a high planting density is used to create landscapes that look mature as required by the landscape industry. A usual consequence is that at very high plant density, thinning operations have to be carried regularly, and plants simply do not grow to their full potential because of space constraint and undue competition. Beck (2013: 92) suggested that constructed ecosystems should be allowed to 'self-design' by accommodating natural ecological processes and leveraging on the capacity of ecosystems to self-adapt. In so doing, it will be expected that energy input to maintain the system will be lower. A direct application of a self-designing strategy is to create planting schemes that allow successional processes to occur, and employ strategies that make use of plant

Fig. 2.6 Shrub planting in narrow planting verges in the centre divider of roads are common in cities: Singapore (*top-left*), Hong Kong (*top-right*), Bangkok (*bottom-left*), Tokyo (*bottom-right*). Apart from adding some greenness to the urban landscape, ecological functions are limited in such UGS. On the other hand, as these are often just abutting the carriageway, frequent trimming is needed, incurring high energy and carbon footprint in the process. The picture on *bottom-left* shows one worker trimming, and another collecting the prunings (*Photo credit* P.Y. Tan)

functional traits in the process, such as nitrogen fixing, species that support avifauna, and forest pioneer species to provide the suitable microclimate for other species to establish. In such a way, landscapes can be shaped dynamically over time (Hwang et al. 2016) and level of maintenance interventions can be reduced.

2.4.4 Principle 4—Ecological Processes Remain Important in Cities

Just as a natural ecosystem is defined by interactions between state factors comprising climate, organisms, topography, parent material, time, humans (Amundson and Jenny 1997), an urban ecosystem can also be defined by groups of state factors, which Tan and Abdul Hamid (2014) organized into natural environmental factors (urban climate, urban biogeochemistry, urban soils, urban biodiversity), built environment factors (buildings, infrastructure, telecommunications), and socio-economic factors (human communities, institutions, heritage, economy). Interactions between state factors are fundamentally mediated by the flows of energy and materials (water, nutrients), and in the case of urban ecosystems, information as well as goods and services. Although not visible to all, ecological processes remain important in urban ecosystems (Flores et al. 1998; Pickett et al. 2011). For instance, when a green field site is replaced with impervious surfaces during land development, the original natural hydrological processes of infiltration, runoff, storage and evapotranspiration have not disappeared, but have merely changed in relative importance. With an increased amount of impervious surfaces, there is reduced infiltration, storage and evapotranspiration, but increased runoff. Concomitant with such alterations in hydrological flows are changes in nutrient flows and energy fluxes due to reduction in latent heat and increase in sensible heat. Thus, ecological flows have not disappeared, but have merely been altered, often to the detriment of human and ecological health.

(a) Design UGS to restore ecological flows
UGS can be seen as a medium to restore ecological flows. The growing acceptance of green roofs, for instance, is partly driven by their use as a means to moderate stormwater discharge through increasing detention of stormwater in urban areas (Locatelli et al. 2014). The emergence of new concepts in urban water management, shown by the adoption of terms such as water sensitive urban design, low impact development, sustainable urban drainage system (Fletcher et al. 2014), are also premised on mimicking of natural hydrological flows through ecologically engineered systems such as bioretention systems, rain gardens, and constructed wetlands. Opportunities should also exist to use UGS to mediate the flow of nutrients in urban areas, although this aspect is far less developed compared to management of water cycle.

(b) Layer ecological functions to achieve multi-functionality in UGS
Just as ecological flows in nature are coupled, such as between energy and water, a useful goal of UGS design is to enable different types of ecological flows to be usefully connected. A clear example is the nexus between water and energy fluxes. While many urban developments incorporate bioretention systems, rain gardens, or constructed wetlands for stormwater management functions, few systems link the objective of management of stormwater to urban climate modifications by enhancing the coupling between water and energy fluxes. The evaporative cooling by plants is driven by the conversion of incoming solar radiation to latent heat during evapotranspiration, but this process is highly dependent on water availability to plants. As bioretention systems, rain gardens, and constructed wetlands are designed to preferentially channel stormwater, through appropriate design, the water can also be channelled to irrigate adjacent UGS and thereby promoting evaporative cooling (Coutts et al. 2013). At the same time, health of UGS can be maintained in periods of water scarcity. Forman's question (2014: 139) 'couldn't creative thinking [through design] and technology capitalize on the considerable rainwater and built surfaces to produce combined solutions for the urban heat, stormwater and water body problems?' in fact also points to the same quest for

multi-functional solutions incorporating UGS to be designed. Additionally, species composition in bioretention systems, rain gardens, and constructed wetlands can be used to support a range of urban biodiversity, such as macroinvertebrates, herpes and avifauna. It is also obvious that although the discussion in this chapter has focused on ecological functions, bioretention systems, rain gardens, and constructed wetlands can also be designed to support a range of socio-cultural functions. Viewed from the perspective of land scarcity in cities, layering of functions to derive multi-functional uses of UGS is also a means to optimize land use efficiency and reduce land for grey infrastructure needs (such as conventional drainage infrastructures).

(c) Integrate ecological functions with built infrastructures
Cities are urban ecosystems dominated by built and social components. Much as there is a high potential and multiple avenues for UGS through a range of ecological and socio-ecological functions to enhance urban conditions, it should be recognized that unless significant progress is also made in the way the built environment is constructed and human consumption patterns moderated, the ecological footprint of cities will continue to exert a strain on natural ecosystems to support human's needs. In other words, although UGS can function as a medium for ecological functions to be introduced to cities, the extent of ecological functions provided is ultimately limited by the amount of vegetated spaces versus the built surfaces in the city. As Tan and Abdul Hamid (2014) highlighted, the dominance of the built component should be seen as an opportunity for design intervention by understanding ecological flows in cities. An example of such intervention is to require buildings to compensate for loss of stormwater detention and infiltration compared to the pre-development state through ecologically engineered stormwater detention tanks and infiltration tanks. In the push for greening of buildings through green roofs and green walls, design should also focus on restoring the pre-development state of evaporative cooling through the use of vegetated surfaces to increase evapotranspiration, and reduce heat intake and storage on building walls. Through appropriate design, there is good potential for UGS and buildings to work in concert to restore hydrological, nutrient and energy flows in urban areas (Tan 2013: 185).

2.5 Conclusion

That UGS is an essential infrastructure in cities is well-accepted, and indeed, it currently forms to varying degrees a key part of the physical makeup of cities. However, it is useful to recognize that the value of UGS cannot be determined by its mere presence, as poor design often means that UGS is either not well-used by humans, or UGS incur higher carbon and energy footprint than the ecological benefits that it should provide. The burgeoning field of urban ecology provides useful conceptual understanding of the nature of cities as urban ecosystems, and principles for enhancing the ecological functions of cities. Similar perspectives can be applied to UGS through such an ecological lens. In this chapter, a role of UGS to enhance ecological functions through deliberate design was suggested and explained using a conceptual model. Four principles selected from the literature for translating urban ecological knowledge into strategies were described. Admittedly, this list of principles and strategies is not exhaustive, and neither is this attempt meant to be exhaustive for a short book chapter of this nature. It is an effort to highlight that urban ecological science can inform the design and implementation of UGS. Importantly too, a current major weakness in the field is that there are inadequate confirmed generalizations that relate to many aspects of UGS to their ecological functions, such as relationships between pattern (configuration, composition, distribution) and heat mitigation, biodiversity support, nutrient recycling, etc. However, the growing emphasis in urban greening worldwide, as many chapters in this book highlight, provides numerous opportunities for scientists, practitioners and policy makers to work in concert to improve the ecological functions of UGS for the betterment of urban conditions.

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Greening Cities
Forms and Functions
Tan, P.Y.; Jim, C.Y. (Eds.)
2017, XIX, 372 p. 51 illus., 48 illus. in color., Hardcover
ISBN: 978-981-10-4111-2