Developing a complementary framework for urban ecology

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Abstract

Cities are characterised by dynamic interactions between socio-economic and biophysical forces. Currently more than half of the global population reside in cities which influence the global biogeochemical cycles and climate change, substantially exacerbating pressures on urban pollution, water quality and food security, as well as operating costs for infrastructure development. Goods and services such as aesthetic values, water purification, nutrient recycling, and biological diversity, that urban ecosystems generate for the society, are critical to sustain. Urban planners are increasingly facing the considerable challenges of management issues for urban ecosystems. Poor understanding of the complementary roles of urban ecology in urban infrastructure, and the functioning of ecosystems and ecological resilience of a complex human-dominated landscape has impeded effective urban planning over time, resulting in social disharmony. Here a complementary framework for urban ecology is proposed, in which ecosystems interact with land use, architecture and urban design - “E-LAUD” - affecting ecosystem and human health, and building on the concept that land uses in urban green areas, road-strips, wetlands, ‘habitat islands’ and urban architecture could synergistically benefit when clustered together in different combinations of urban landscapes. It is proposed that incorporation of the E-LAUD framework in urban planning forms the context of a new interdisciplinary research programme on ecological resilience for urban ecosystems and helps promote ecosystem services.

Key words: urban ecology; urban planning; landscape design and architecture; ecological resilience; complementary framework

Introduction

Cities are an increasingly complex spectrum of human-dominated architectural infrastructures and ecosystems comprising green patches and wetlands (Bolund and Hunhammar, 1999). Currently as much as 50% of the global population live in cities (Grimm et al., 2008). High population growth rates and population increases are predicted from 7 billion today to 9.3 billion by 2050 and 10.1 billion by 2100 (Lee, 2011). Urban areas are expected to expand rapidly, leading to more than 60% of global populations living in cities by 2030 (Lee, 2011). Humans, at the centre of structural phenomena, modulate urban ecosystems for a range of services including food, energy, water and waste recycling (Carpenter and Folke, 2006). By doing so humans also profoundly alter species richness, composition and diversity through fragmenting habitats, introducing exotic species and changing land use and land cover patterns (Williams et al., 2009). Hough (2004) explicitly describes the relationship between cities and natural processes. Alternative values, such as attitudes and cultures based on ecological insights, may offer tremendous possibilities of constructive relationships between nature and humans. Urban designs may invite conflicts as they potentially risk affecting natural processes, while conversely the exploration of creativity and opportunities offer potential avenues to sustainable cities (Hough, 2004). In this regard, Waldheim (2006) further brings an excellent discourse on landscape urbanism, which describes urban environment as a disciplinary realignment within natural and architectural landscapes. This concept has revolutionized the narrow view of the classical urbanism, where a city was regarded as an architectural design in a condensed space encompassing the buildings, outdoor public spaces, and streets. Today, landscape is emerging as a model for urbanism, activating space and time, and leading to superior urban spaces as desired by society. Landscape urbanism is thought to be layered in a way that should reflect non-hierarchical, flexible, and strategic elements that are essential for design. Waldheim (2006) argues that by integrating landscape urbanism with design, the area in which the city resides greatly benefits the people who are using it. However, there are issues interfering with the concept of promoting landscape urbanism. In Australia alone, for example, more than 1,700 species and ecological communities are reported as under threat or at risk of extinction, these are focused around urban areas, which have disrupted and destroyed patches of the native landscape (Figure 1; DSEWPaC, 2010). This is only the tip of the iceberg however, for every known species that is placed on the ‘at risk’ register there are many more that are affected by destruction of habitats and other threats.

Further, cities produce as much as 78% of greenhouse gas (GHGs) emissions, as well as creating urban ‘heat island’ effects which contribute significantly to global climate change, followed by increased disparity among ecosystem services, exacerbated urban pollution, reduced human health, altered water quality and food security (Arnfield, 2003; IPCC, 2007; Rosenzweig et al., 2010). Urban reliance on energy, resources and information to function, as well as uptake, transformation and storage of materials, and discharge of waste products, increases the interactions between socio-economic and biophysical forces (Cadenasso et al., 2006; Peters et al., 2008). For example, Australia’s per capita ecological footprint in 2007 was (and continues to be) one of the largest in the world, sitting comfortably in the global top ten – 6.9 global hectares (Global Footprint Network, 2010; Figure 2). Unless the global ecological footprint is stabilized there will be a tipping point, in the not too distant future, when the demand will outstrip the resource supply or bio-capacity (Meikle and Elkadi, 2012). Many cities are rapidly transforming into alternative paradigms of patterns and processes, working to address issues of sustainability and adapting to become new urban systems (Carpenter and Folke, 2006). For instance, since the 1970s, the per capita food, water and material consumption in Hong Kong have surged, and the pollution by fossil fuel emissions, atmospheric CO_2 outputs, municipal solid wastes and sewage discharges have become substantially higher (Warren-Rhodes and Koenig, 2001).

Urban design and planning have become considerable challenges as the values of spatial differentiation in urban landscapes are largely disregarded. There is limited consideration of the rapidly changing patterns and processes of urban ecosystem functions as a result of variations in growing human perception, choice, and action driven by political, economic and cultural decisions (Pickett and Cadenasso, 2008). There is a comprehensive knowledge gap on how urban ecosystems function within the complex mosaic of urban design and infrastructure such as building, landscape architecture and civil engineering, and the 'complementary' role they play in urban landscapes, fundamental components of urban planning. 'Complementary' stands for how mutually urban ecology and infrastructure developments can full-fill each other's deficiency. For example, the flora and fauna, along with urban building and surfaces, road and railway networks, are principle elements of urban structures that yield significant benefits both to local urban residents and the wider community, as well as creating and maintaining the systems 'down-stream' by providing significant refuge and networking through inter-habitat-connectivity (Halpern et al., 2008). Urban infrastructures, on the other hand, would act as habitat analogues for ecology (Lundholm and Richardson, 2010). Urban design and planning would also collectively benefit from an understanding of urban ecosystem structures and functions (Niemelä, 1999a).

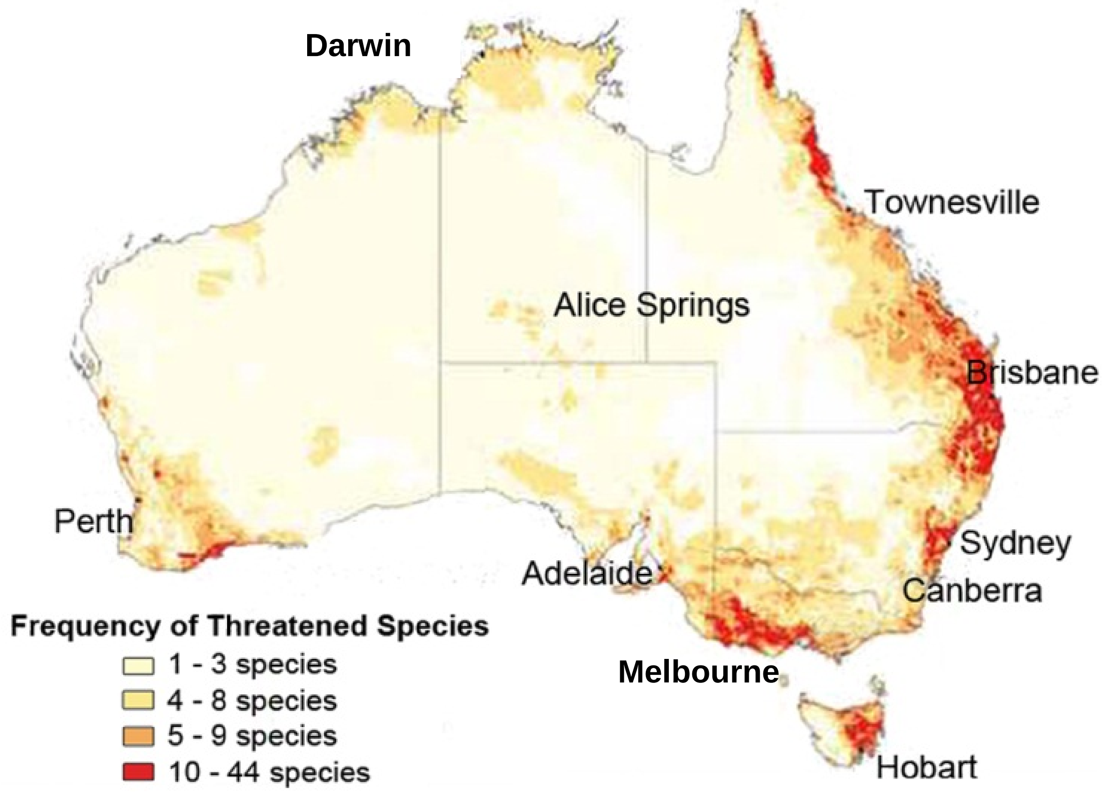

Fig. 1. Distribution of species listed as threatened under the Environment Protection and Biodiversity Conservation in Australia.

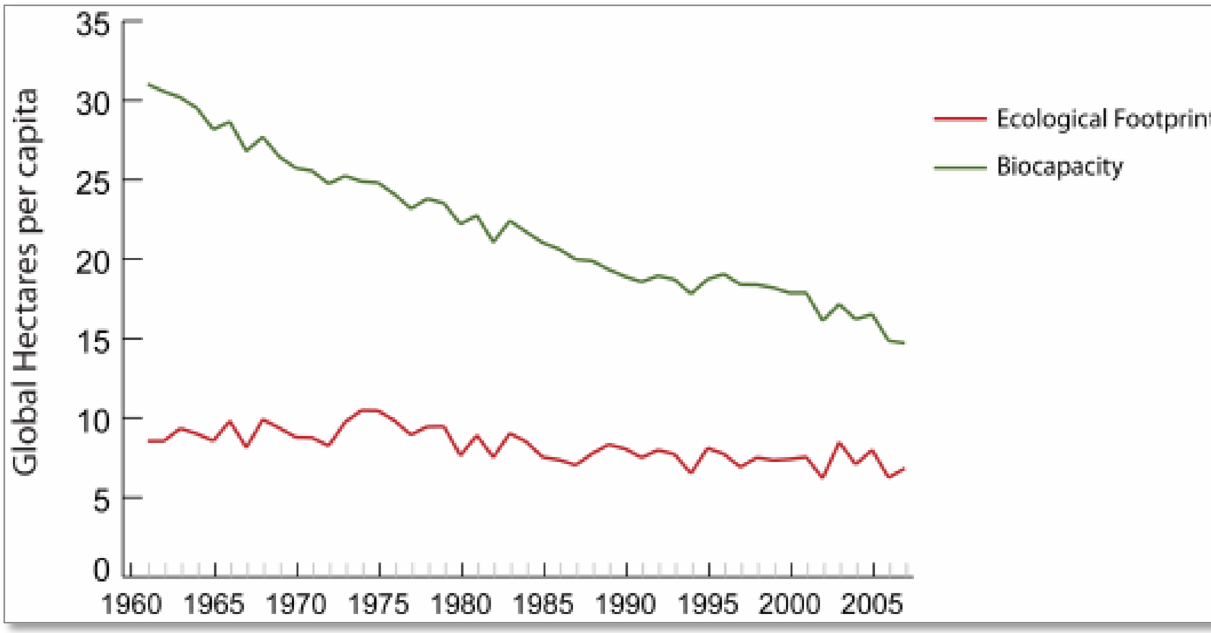

Fig. 2. Per capita resource demand (ecological footprint) and resource supply (bio-capacity) in Australia since 1961 (Global Footprint Network, 2010).

Elements of "green infrastructure" comprising both natural and artificial habitats contribute to urban ecosystem health. For instance, urban and peri-urban habitats increase vegetation cover, and stream communities contribute to biological diversity and conservation, maintaining the integrity of systems and providing a physical basis for ecological networks (Hofmann et al., 2012). Human-designed ecological engineering (e.g. an artificial fish ladder in the river) helps overcome management issues of artificial habitats, makes urban ecosystems suitable for endemic fish species and assists in establishing a greater dispersal mechanism (Lundholm and Richardson, 2010). Indicator-based information entropies would reflect functioning, metabolism and sustainability of urban ecosystems (Zhang et al., 2006). The roles of urban designers and planners are therefore vital for achieving sustainable development of the city by understanding and maintaining 'green infrastructure' and urban ecosystem functioning to meet the growing demands of urban people for quality life space and public appreciation of infrastructures and natural environments. Learning cross-scale interactions and feedback mechanisms between urban design and human actions on ecosystem functions along temporal and spatial scales are significant at a time of increased demands in effective urban planning (Pickett and Cadenasso, 2008).

Development of a conceptual framework or theoretical model has the potential to resolve issues of management and sustainable use of urban landscapes to establish goals and evaluate outcomes, and provide useful inputs to urban growth management strategies (Anderson, 2006). Linking ecological and social systems is fundamental for sustainability of urban populations (Zipperer et al., 2011). For example, the Long Term Ecological Research (LTER) in the US suggests that for urban ecological systems a broader range of structural and functional relationships are often significant (Alberti, 2008; Pickett et al., 2009). Understanding the relationships between social status and awareness of environmental problems, and between human tribes or race and environmental hazards can produce better outcomes in urban ecosystems values (Grim et al., 2000; Alberti, 2008; Picket et al., 2008). Various conceptual frameworks and empirical models have been developed for land use change patterns in the context of species diversity, riparian function, and carbon and nitrogen dynamics in urban watersheds (Pickett et al., 2008; Niemelä et al., 2009; Pickett et al., 2011). However, the majority of these models are bio-centric in nature, focusing mainly on ecological components with limited accounts given of decision making processes or effects of social drivers on ecosystems (Zipperer et al., 2011). A few alternative models, based on the theory of ecological economics, have also attempted to address the interactions between humans with themselves and humans with their environments (Parker et al., 2003). However, these models may not be able to address the core issue of urban ecosystems and sustainability. Ecosystem resources in these agent-based models are predominantly constrained by human-imposed policies and institutional regulations and norms rather than being provisioned to function in a reciprocally interactive fashion (Parker et al., 2003).

In urban environments, ecological resilience frameworks have become an increasingly successful metaphor to achieving sustainability goals as it allows integration of ecosystem functions with social dynamics (Pickett et al., 2004; Pickett et al., 2009). Resilience in ecology theorises the manner in which ecosystems can return to their original state after being disturbed (Carpenter and Folke, 2006). In urban ecosystems, the ecological resilience is described as the capacity of a city to persist without changing its basic structure, function and identity. Even if an unforeseen shock fundamentally alters or erases the identity of a city, the resilient city would withstand such impacts (Wu and Wu, 2011). Ecological frameworks have become significant in reducing lags between social patterns and urban ecosystems. For example, the links between vegetation, the biogeochemistry of lawns, ecosystem nutrient retention, and social-biophysical feedbacks have all suggested that continuous refinement of conceptual frameworks are able to address the reciprocal nature of ecological and social system interactions (Picket et al., 2009). This study aims to develop a more refined framework, which is complementary in nature and acts as a reciprocally interactive function amongst ecosystem, land use, architecture and urban design (E-LAUD), proposing to fulfil each other's voids for urban ecosystems. Such a framework mainly benefits the resource managers and urban designers by facilitating a better understanding of the complex interactions between urban ecology and urban design. Incorporation of the E-LAUD framework in urban planning is expected to construct new interdisciplinary as well as trans-disciplinary (integrative) research questions which can help form a resilient society through promoting urban ecosystem services. Fry et al. (2007) proposed the idea of using integrative research in urban ecosystems, where researchers spend a greater proportion of their professional careers in integrative projects composed of various disciplines; having direct exchanges with stakeholders and other non-academic participants which eventually help solve management problems in multifunctional landscape environments.

2. Complementary functions of urban ecosystems

Urban ecosystems play a complementary role to architectural designs. Characteristic of patch dynamics, proximate wildlife habitats and water ways can make substantial contributions to goods and services, and ecological resilience of the city directly and indirectly through inter-connectivity, dispersal and pollutants filtering and entrapping mechanisms.

2.1. Patch dynamics

Urban ecosystems are characteristic of fragmented patches of greenery, wetlands and reservoirs embedded within a complex matrix of physical and social infrastructures (Hofmann et al., 2012). Patch structures (size, composition, persistence and interconnectivity) are regarded as crucial for maintaining species survival and ecological conditions (Pickett et al., 2004). Species colonization in less or non-populated patches is affected by the properties (i.e. size, shape and habitat quality) of the highly populated patches, properties of the potential source populations of migrants, and the properties of the intervening habitat matrices (Moilanen and Nieminen, 2002). Species richness in single-habitat patches (alpha diversity) is often found to be significant in urban habitats, as the urban habitats offer suitable environmental gradients for many dispersing species (Niemelä, 1999a). The diversity of activities conducted by users of urban areas can create, and maintain, a wide variety of habitats and biodiversity, with urban landscapes potentially hosting rare and threatened species (Eversham et al., 1996). Species require movement between patches in order to obtain critical resources, including space for foraging, roosting and breeding. Urban patches also resemble ‘intermediate disturbance hypothesis’ indicating that species richness of some biota is higher at intermediately disturbed sites than heavily disturbed or undisturbed ones (Farinha-Marques et al., 2011; Pickett et al., 2011). Consequently, at landscape level, species composition among patches (beta diversity) would become higher in urban areas (Rebele, 1994). Urban patches aligned with architectural structures strongly support refuges for wildlife and help species supplement resource intakes (Colding, 2007). However, urban development adversely affects patch dynamics by altering size, shape, interconnectivity and the composition of biota. Unplanned urban developments have consequences for the physical transformation of patches, resulting in differential responses from ecosystems to changes (Alberti and Marzluff, 2004).

Spatial heterogeneity within an urban ecosystem is generated by both biophysical and human processes (Pickett et al., 2004). Interactions between socio-economic and biophysical forces have implications for patch dynamics, and patterns and processes of energy supply, uptake, transformation and storage of materials, and discharge of waste products across temporal and spatial scales (Peters et al., 2008). Industrial emission via atmospheric deposition, and release of sewage-derived inorganic and organic, carbon, phosphorous and nitrogen-related compounds, stormwater runoff and hydrocarbons from individual patches further enrich contaminants in urban ecosystems (Tran et al., 2002). Consequently disturbances in ecology are a discrete event in space and time that disrupts ecosystems, communities or population structures (Carpenter and Folke, 2006). Natural disturbances are often modified in cities by human-utilized barriers which potentially reduce the heterogeneity of natural habitats (Pickett et al., 2004). Human sources of heterogeneity include the introduction of exotic species, modification of landforms and drainage networks, and the construction of extensive infrastructure (Pickett et al., 2004). These activities would further result in differential connectivity patterns, for example in river–creek networks within the urbanised landscapes, the differences in connectivity can significantly influence ecosystem persistence by reducing the movement of food resources and biological dispersal across fragmented patches (Anderson, 2006).

2.2. Proximate wildlife habitats

Urban ecosystems provide immeasurable aesthetic and cultural values to urban communities as they increasingly serve as proximate wildlife habitats (Kim and Zhou, 2012). Small mammals, birds including dove (*Columba sp.*), house sparrow (*Passer domesticus*) and numerous species of songbirds, herpeto-fauna and squirrels have successfully acclimated to urban environments, in part because of their ability to use highly fragmented habitats (Ditchkoff et al., 2006). Often the fragments of natural vegetation and wetlands in urban areas may be too small or even too isolated to support species-specific habitats. However, habitats associated with ruined infrastructure, barren lands, shrubs and submerged macrophytes of constructed wetlands can influence the abundance of a range of terrestrial and aquatic species, their diversity through providing nesting grounds (Hofmann et al., 2012). The pilings, pontoons, as well as natural rocky reefs can also become significant habitats for sessile plants and animals (e.g. epibiota) (Connell, 2001). The wildlife populations residing and reproducing in close proximity to high human densities have a substantial ability to maintain biological diversity and aesthetic values of the urban areas (Ditchkoff et al., 2006). However the ecological effects of habitat fragmentation are complex, diverse and pervasive in urban areas as fragmentation affects animal and plant populations via a number of interacting pathways (Bolger et al., 2000). For example, isolation by intervening human-modified matrix impermeable to dispersal can affect population sizes and rates of stochastic extinction substantially (Williams et al., 2009). Human-induced habitat alterations have forced species to colonize in disturbed or newly created habitats leading to primary, secondary or intermediate types of succession (Rebele, 1994). In cities, edge effects or spill-over effects are also common from the surrounding human-modified matrix causing physical gradients of light, moisture and wind (Bolger et al., 2000). Suburban habitats associated with edge effects will be continuously infiltrated by introduced species (e.g. coyotes, *Canis latrans* and white-tailed deer, *Odocoileus virginianus*), gradually replacing the habitats of endemic wildlife (Rebele, 1994). The direct effects of area reduction, isolation and edge can lead to secondary, cascading or trophic effects where interactions between predators, parasites, competitors, resource species or mutual species are potentially affected (Bolger et al., 2000).

2.3. Island biogeography

Although there have been some criticisms of island biogeography theory, for example, Wu (2008) regarded this a 'flaw' in its practicality, urban ecosystems are still widely considered part of island biogeography models and increasingly used for conservation and management of ecosystems (Colding, 2007; Marzluff, 2008). The island biogeography principle examines the factors that affect the species richness of isolated natural communities (MacArthur and Wilson, 1967). In urban settings the interaction of abiotic, biotic and cultural factors produces a range of isolated 'habitat islands' with considerable variations in size, and degree of disturbance. Every city is a collection of these 'habitat islands', where transformation of ‘natural’ habitats would continuously occur. Golf courses, cemeteries, parks, playgrounds, utility corridors, railroad tracks and marshalling yards, roadsides and median strips, garbage disposal sites, sewage treatment plants, city-centre high-rises, old and new residential areas dominated by apartment blocks and condominiums, and parking lots are all part of a modified form of urban landscape (Davis and Glick, 1978).

Functioning of urban ecosystems is strongly determined by the nature of these ‘habitat islands’ and how they are connected, ensuring that organisms maintain their diversity and populations through mobility and outside recruitment as well as the availability of food and shelter, the degree of exploitation or disturbance. For instance, changes in population size and species number may occur rapidly in a single 'habitat island', while other ‘habitat islands’ can behave differently due to variations in disturbances and landscape structure (Kim and Zhou, 2012). However, human actions greatly influence rates of colonization and extinction of species across the ‘habitat islands’. Urbanization may bring a progressive decrease in species richness as a result of the reduced biogeographic functions of ‘habitat islands’, leading to biotic homogenization, a form of genetic, taxonomic or functional similarity amongst biota (Olden, 2006). Humans juxtapose a variety of land covers, and directly or indirectly introduce species outside of their native ranges (Williams et al., 2009). As a result, the effects of habitat loss and exotic species on species diversity are significant. However, cities may not necessarily be biotically homogenized as the effects of invasion may be more significant on abundance and distribution of native species than on species diversity (Collins et al., 2002). Species colonization is reduced by the way people transform natural habitats into urban infrastructure, put barriers between urban habitat islands and create disturbances in dispersal. Extinction of species may occur in response to land cover change or new selective forces applied by either natural climatic regimes or by predators, diseases, and competitors (Harvel et al., 1999). However, the biotic homogenization may not only be the result of anthropogenic causes, this could also be influenced by a combination of biogeographically-defined anthropogenic and historical factors (La Sorte et al., 2007).

2.4. Buffering

Urban ecosystems are regarded as buffering strips against urban pollutants and act as thermal habitat patterns and resource availability for urban wildlife. For example, the constructed wetlands have potential for storing and filtering runoff (Ellis et al., 1994). The nutrient and heavy-metal-enriched runoff in wetlands and parks is filtered naturally through impervious soil, microbial decomposition as well as through uptake by aquatic macrophytes (Kohler et al., 2004). In addition, humans will benefit from macrophyte-induced water filtering processes in wetlands, contributing to clean water amenities and environments. In coastal urban ecosystems, primary producers act as the ‘coastal filter’ for eutrophication (Meyer-Reil and Köster, 2000). Plant-mediated nutrient cycling potentially increases as eutrophication induces a shift in dominant primary producers (McGlathery et al., 2007). Terrestrial and wetland bird species nesting in green patches and wetlands within residential housing and allotments constitute effective pest-regulators on agricultural cultivars. These green patches and wetlands attract insect-controlling birds and act as a buffer against outbreaks of various pest populations (Colding, 2007).

Urban ecosystems also have a ‘heat islands’ effect which establishes a buffering capacity against cold winters, and extends the growing seasons in cities across temperate zones. In drier cities, urban warming increases stress in plants leading to lower fibre quality, conversely, irrigated green spaces can buffer against high temperatures via evapotranspiration (Shochat et al., 2006). Evergreen urban environments attract rural wildlife exposed to hostile dry climates (Parris and Hazell, 2005). However, urban ecosystems are becoming increasingly vulnerable to changes in demographic and land use patterns. The shifts from forest to agricultural, suburban, and urban land use accelerate delivery rates of nutrients from both known and unknown-point sources (e.g. wastewater, agriculture, poultry farms, ground water) across terrestrial and coastal margins. This can lead to the loss of favourable vegetation such as submerged macrophytes in wetlands, seagrasses in estuaries, harmful micro- and macroalgal blooms, shifts in food web structure, increased anoxia/hypoxia, and changes in organic matter burial and degradation (McGlathery et al., 2007). Consequently the critical services, including drinking water, fiber, fish and shellfish production, as well as human recreational activities are affected (Worm et al., 2006).

3. Developing a complementary framework for urban ecology

The complementary framework is based on the notion of 'ecology of cities'. Cities are the rich nodes of civilization, the cultural and commercial centres, and also the ecological phenomena at larger geographic setting. Cities are a complex ecosystem which depends not only on internal biophysical exchanges but also on the external provision of energy and materials supply. The far-reaching effects of energy and material inputs and outputs constitute the ecology of these human-dominated complex ecosystems (Grimm et al., 2008). Literature presented on ecology and cities has widely reflected on how the city is viewed in the context of ecological change as "Ecology of the city" or the perception of the city in the context of ecological change as "Ecology in the city (please see glossary for detail).

The complementary framework recognizes the complex interactions affecting ecosystem health and human health in urban areas and builds on the idea that land uses in naturally existing and urban green areas could synergistically interact to support biodiversity when clustered together in different combinations of landscape architectures and urban designs (Cadenasso et al., 2006). Innovative urban designs link ecology with the ongoing transformation of urban systems. Quality of life, human health, the public appreciation of ecological processes in cities, and scientific understanding of all of the above are a part of a complementary framework of urban ecosystems, enhanced by participatory approaches of stakeholders in ecology and urban design (Pickett and Cadenasso, 2008). Participatory approaches of ecology and urban design promote landscape complementation functions for critical ecosystem processes that urban planners can use to improve the ecological resilience of the city (Colding, 2007). Hence 'city' as a whole requires a broader integrated framework that complements a range of disciplines, including biological, physical and social that are incorporated successfully in urban design and planning.

4. Incorporating the complementary framework in urban planning

Spatial differentiation in urban areas is essential for a range of disciplines including geography, social science and urban design (Pickett and Cadenasso, 2008). Ecology in the city focuses on patches of both physical and biological environments including soil, water, plants, animals and wildlife resources as well as their connection to urban design and building infrastructure (Pickett and Cadenasso, 2008). The biological diversity and assemblages, along with urban building and surfaces, are principle elements of urban structures benefiting substantially local urban residents as well as ‘down-stream’ systems including water, air and pollution flows. In spite of an increased interrelationship between biological diversity and assemblages and architecture infrastructure, the ecological phenomenon in urban areas is poorly understood. The concept ‘city as ecosystem’ is not yet realized fully (Grimm et al., 2000). As a result there is a huge gap in understanding the interface between ecology and infrastructure by ecologists and urban planners in the context of sharing knowledge and skills on sustainability (Alberti and Marzluff, 2004). Forefront knowledge required urgently is ecological patterns and processes, how these processes are related to urban populations in the context of land use change patterns and resource consumptions, and how these resources are eventually perceived by urban society (Alberti, 2008). In order to address these issues, this study proposes incorporation of an integrated framework on Ecology, Land Use, Architecture and Urban Design (E-LAUD) into urban planning. The E-LAUD framework has overarching effects, and potentially complements a range of urban planning issues and improves ecological resilience by addressing different interdisciplinary and trans-disciplinary questions in urban ecology (Fig. 3). Such a framework is considered useful for ecologists and planners since development of more refined and realistic ecological models will lead to greater success in finding solutions to environmental problems in cities (Grimm et al., 2000). Integrated models are efficient for urban land use arrangements by preventing development pressure on urban fringe, reducing resource use, emission of pollutants and minimize impacts on aquatic and terrestrial ecosystems (e.g. Alberti et al., 2003). It has been argued that the multifaceted framework and the growing urban knowledgebase help identify pressing research needed to resolve various urban issues (Pickett et al., 2011). This complementary framework will form a new insight into interdisciplinary as well as trans-disciplinary studies to assist urban ecologists and designers in managing urban green patches and improving biological diversity in rapidly changing urban landscapes; application of this framework will help configure urban greenbelts across road networks and improve habitat inter-connectivity; this will also consider placing urban 'habitat islands' as wildlife buffer strips and urban wetlands as urban pollutant traps. Further, this framework will consider the role of urban wealth and innovation as an important tool for decision making in urban planning through the exchange and use of ideas, tools and information.

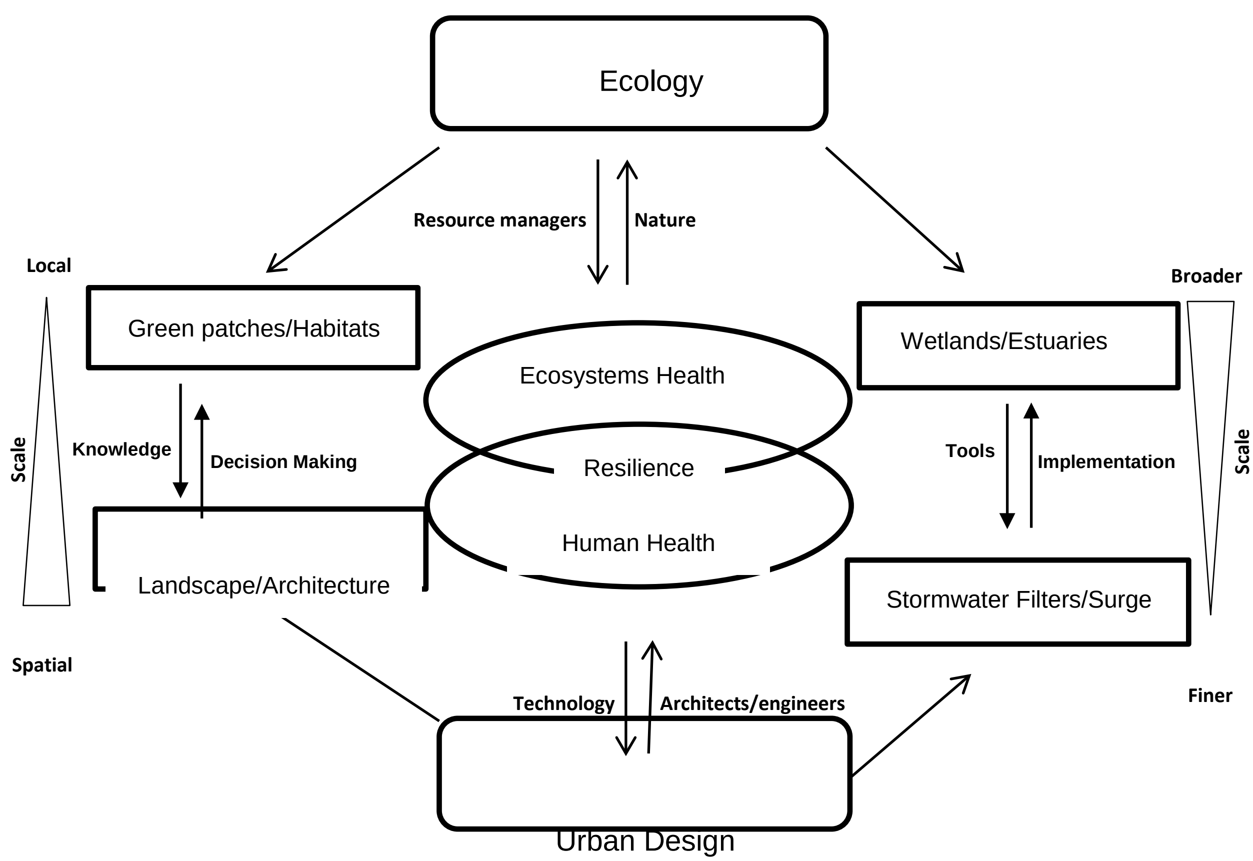

Fig. 3. A complementary framework for urban ecosystems based on Ecosystem-Land Use, Architecture and Urban Design (E-LAUD). The ecology and urban design in the opposite boxes represent interaction between nature and infrastructure. The framework has overriding influences on ecological resilience between ecosystem health and human health. Designing landscape architecture for building, roads and railway network as well as constructing wetlands and reservoirs are significant parts of urban development. Mean time urban green patches, urban greenbelts, wetlands and estuaries all play an important role for urban ecologies by providing a refuge for urban wildlife as well as by filtering urban pollutants and defending storm surges. On the one hand, technological developments continue to influence the state of human health and on the other hand, the state of ecosystem health is largely determined by natural system maintained within the urban landscape. Ecological resilience is usually dependent on the magnitude of the status of both human health and ecosystem health. Urban wealth and knowledge will continue to help developing tools, infrastructure, technology and innovation and better management techniques for urban design and landscape planning as well as urban health and education. For instance, in the case of urban wetlands, design of effective stormwater filtering traps and better implementation can help promote ecosystem health; similarly, the exchange of knowledge through the use of geographic information system (GIS) amongst various stakeholders (resource managers v architects) can help effective decision making processes for urban resource managers on urban landscape management. However, in each case, either wetlands or green patches, the scale (finer versus broader or local versus spatial) can play a determining role on patterns and processes of urban ecologies. For example, resilience would vary individual or local to landscape or continental level green patches, while the response of broader scale (large in number) wetland/estuaries would be higher for stormwater surge filtering capacity than finer (small in number) scale wetlands (see also Pickett et al., 2009).

4.1. Urban green patches complement land use patterns

In the E-LAUD framework, urban planners will consider incorporating multiple factors that shape patches and ecological connectivity of the city in order to improve ecological resilience. Individual patches have the potential to provide ecosystem services through biological conservation. Large quantities of species in individual patches often have similar ecological roles, increasing potential community organisations and upholding higher ecological resilience and services (Anderson, 2006). Creation of patch maps based on population density, zoning, time of development, the distribution of income, race, or education levels of residents, and land use practices is intrinsic to improving the complementary function of green patches to land use patterns. Each map can be a snapshot of the system structured by one variable or a suite of variables, where each class type is defined by the combination of attributes of ecology and built environments describing the influence on ecosystem functions, such as biodiversity, carbon sequestration and pollution storage and transport. Comparing the patch structures that emerge from different perspectives of class types can provide insight to the structure and function of an integrated system (Colding, 2007). Further, the time series data on spatial heterogeneity of land use such as patch richness, frequency, and configuration of the system can help quantifying changes in patch size, type and configuration, as well as changes in the associations of ecological and social patch types and the improvement of dynamics of urban patches and their connectivity (Colding, 2007). However, understanding patch configuration and richness also requires the assessment of highly complex, self-sustaining structures, whether cells, organisms, or communities, and their networking ability within the patches (Bettencourt et al., 2007). The E-LAUD framework will consider incorporating a better understanding of the system networking ability through developing a range of refined models (e.g. Pickett et al., 2004). For example, Colding et al. (2006) analysed the role of urban green areas managed by local user groups in their potential for supporting biodiversity and ecosystem services in rapidly growing city-regions of Stockholm, Sweden, with a focus on allotment areas, domestic gardens, and golf courses. The use of spatial data on three urban green areas in GIS modelling showed increasing ecosystem functions and services provided by these urban green areas as a result of the higher incorporation of locally managed lands, and their stewards and institutions. The urban managers and designers involved in the project were mutually benefitted. Such co-managed urban designs also showed potential for maintaining urban biodiversity and reducing transaction costs in ecosystem management (Colding et al., 2006).

4.2. Urban greenbelts complement transport network

In the E-LAUD framework, urban planners will consider incorporating green-belts and streams as habitat corridors for urban ecosystems. The spaces beside the road and rail network and building infrastructure are often designed to link with wetlands and other green patches within the city as well as rural habitats, a ‘large reservoir’ outside. The use of urban-rural gradient analyses has shown the link between the outside reservoir and inner populations (McDonnell and Hahs, 2008). Greenbelts facilitate movements and ensure colonization of isolated natural areas, while streams form natural corridors in urban areas. However, construction of road/rail networks, residential housing and industries displace particularly sensitive native species by disconnecting corridors and stream networks. The integrity of the patterns of stream communities across watershed areas has been substantially altered by urban development (Alberti et al., 2007). Urban planners will consider greenbelts as corridors for movement of mammals, birds and reptiles, and these greenbelts potentially inter-connect with river network in the watershed.

Road strip corridors are often attributed to noise and traffic mortality, and the removal and fragmentation of greenbelts and abstraction of river networks is known to affect species richness and the abundance of flora and fauna (Carbó-Ramírez and Zuria, 2011). This would become significant for migrating birds and reptiles in protecting themselves against predators including those from above (Davis and Glick, 1978). Greenbelts also provide breeding habitats for several edge species (Savard et al., 2000). Managers working for urban ecosystems may consider using E-LAUD framework for the maintenance of habitats and connectivity to promote survival of sensitive species that are potentially exposed to urban infrastructural and environmental change (Fig. 3). For instance, Acevedo-Whitehouse and Duffus (2009) reported that climate related shift in pathogen and host ranges and pathogen spread out from humans and domestic animals can increase exposure to new diseases to wildlife. Similarly, changes in habitat size or quality can lead to a reduction in prey population sizes, and increased competition for resources which in turn augment starvation, malnutrition, disease and death (Acevedo-Whitehouse and Duffus, 2009). Connecting greenbelts, streams and ‘habitat islands’ is significant since ‘habitat islands’ are important population (both humans and wildlife) reservoirs.

Tunnels and bridges can also increase the permeability of roads by allowing the safe passage of fauna across the road, and the use of appropriate fencing to reduce the mortality rate of wildlife when traversing busy urban roadways (van der Ree, 2006).

However, the fate of smaller 'habitat islands' in urban ecosystems is increasingly precarious as nearby larger population 'reservoirs' are less likely to be available in the city, leading to increased extinction rates which exceed species colonisation (Davis and Glick, 1978). The rate of loss largely depends on the effectiveness of local conservation strategies. The E-LAUD framework will focus on conservation of those species threatened by loss of habitats and affected by human actions, by considering the area requirements of the species able to disperse through greenbelts and other corridors. For example, Carbó-Ramírez and Zuria (2011) explored bird communities in different types of small urban and suburban green spaces (<2 ha) in order to understand refuge of birds on varying structures and the habitat and landscape features in the city of Pachuca, Mexico. Bird species richness, abundance and community composition were affected by the characteristic green space areas adjacent to landscapes covered by urban structures and vegetation, and human disturbance variables such as traffic of pedestrians, vehicles and noise levels. Urban ecosystems managers would like to achieve increased species richness and composition of plants and animals across the urban green-belts adjacent to road networks and liaise closely with road network infrastructure designers and engineers. Higher bird species richness in parks and gardens, and lower richness in road strip corridors, where more noise and traffic are experienced as shown in Carbó-Ramírez and Zuria (2011) indicates the increasing significance of complementary frameworks in urban ecosystem management through a liaison between urban resource managers and infrastructure designers.

4.3. Urban ‘habitat islands’ complement human and wildlife refuges

The E-LAUD framework will consider urban ‘habitat islands' as complementary refuges for humans and wildlife in promoting social and ecological resilience, a condition with increased ecological values and services. Increased spatial areas for wildlife refuge are considered significant for rich species diversity within the ‘habitat islands’ and the ecosystem services to be utilized by urban populations. These ‘habitat islands’ often act as a human-ecosystem framework, where humans and ecological processes are reciprocally interactive (Pickett et al., 2004). Urban ecosystems of small rural and coastal cities may function better than large cities as smaller urban ‘habitat islands’ can have optimal human care, and also potential to acclimatize plants and animals to environmental change faster (Davis and Glick, 1978). Smaller ‘habitat islands’ can be a significant recruitment ground from the countryside population reservoir through corridors as these corridors are also short and effective. Urban planners should consider the function of individual-urban ‘habitat islands’ during urban design. For example, in large cities, the inner individual 'habitat islands' are separated from each other and from the rural matrix, corridors are usually larger but less effective than those in small cities (Davis and Glick, 1978). The E-LAUD framework will consider proximate habitats for both bigger and smaller organisms with the view that most species are associated with increased habitat inter-connectivity and human appreciations (Savard et al., 2000). Through the use of this framework urban resource managers will be able to increase the volume and diversity of habitats, for example, vegetation areas in a city would increase abundance and diversity of species of wildlife across spatial scales (Kim and Zhou, 2012). Expansion of marine and freshwater wildlife habitats beyond existing boundaries would assist in completing life-cycle stages, nesting and successful terrestrial hibernation of critical species (e.g. turtle) (Burke and Gibbons, 1995). Buffer size requirements for wildlife, however, have typically been established by scientific knowledge and political compromises. There is still a huge knowledge gap on wildlife buffer zone management in urban areas. Unlike rural areas, the outskirts of cities tend to displace natural wildlife habitats with time and space as a result of infrastructure developments. In E-LAUD framework, the urban resource managers will consider significance of buffering for ecological resilience (Fig. 3). For example, a buffer of 15 m width is reported to have useful to protect wetlands and streams under most human-dominated conditions (Castelle et al., 1994).

4.4. Urban wetlands complement pollution and storm surge

The E-LAUD framework will ensure improved water quality in the city. Urban wetlands, both natural and constructed, act as stormwater retention basins. Vegetated buffer zones are considered significant in order to minimize erosion or trap sediments in surface runoff thereby decreasing phosphorus loading in surface water (Vought et al., 1995). Wetlands of rich macrophytes and anaerobic sediments have a better retention and degradation capacity for introduced materials by removing significant amounts of suspended solids, organic matter, nutrients, heavy metals, trace elements, pesticides, and pathogens through chemical, physical, and biological processes (Kohler et al., 2004). Excessive nutrients and pesticides in wetlands can lead to degraded water quality, stimulated algal blooms, and eutrophication. Pesticide runoffs can also potentially affect off-target species (McGlathery et al., 2007). While nutrient and pesticide management is largely handled by soils in the terrestrial system; the wetlands offer a means of containing these materials if they do migrate into the drainage water (Kohler et al., 2004). In the E-LAUD framework, urban resource managers and infrastructure designers consider utilizing natural and constructed wetlands and river channels to maximize water quality through increasing their holding capacity during storm surge events, and also through minimizing stormwater run-off outputs during non-storm periods. A better management strategy, including vegetation buffering and using improved tools and technology has often been considered accountable in such framework (Fig. 3). For example, in US cities, uncontrolled stormwater runoffs from areas with impervious surfaces exceeding 10% can lead to a significant decline in water quality and the health of urban aquatic ecosystems (Walker, 2001). Residential suburbs with typically high levels of impermeable surface drains increased amount of stormwater, and enlarges five times of channel areas than with less impermeable surface, and endures increased flooding. Traditionally managed public entities for urban water resources only focus on engineering benefits with limited provisions for a hydrological cycle. Adequate design, coupled with long term provision of maintenance of constructed channels and wetlands, however, endures water quality and reduce flooding (Walker, 2001). Achieving the goal of sustainable water quality management and ecological resilience in cities, a comprehensive water resource management is essential that combines water supply, sanitary sewage, stormwater drainage, and wildlife protection. The E-LAUD framework will endeavour to engage a range of stakeholders, including engineers and resource managers, to establish an integrated approach to watershed-scale at a local level.

4.5. Urban wealth and innovation complement information technology

Cities offer both opportunities and challenges toward future scenarios of urban ecosystems and sustainable development (Alberti et al., 2007). Cities offer economic and infrastructure development, and facilitate the optimized delivery of social services, such as education, health care, and efficient governance (Bloom et al., 2008). Human adaptation of urban living puts pressures on cities to utilize natural resources resulting from obvious changes in land use. However, cites reflect an increased division of labour and the growth of occupations that build wealth and innovation (Bettencourt et al, 2007). Cities are often regarded as a 'learning loop' (Pickett et al., 2004), where many cities have viewed knowledge, innovation and creativity as keys to development and economic prosperity, and filtered these views into future developmental strategies (Bloom et al., 2008). Knowledge-based capital has high levels of connectivity to the regional and global economy, generating virtuous circles of competitiveness, enabling expansion and innovation (Simmie, 2003). An integrated socio-biophysical system of consumers of energy and resources, and producers of artefacts, information, and wastes in cities would attract knowledge-generating infrastructures (e.g. universities, R&D institutes) and researchers of global connections. High levels of research and development expenditure would promote science and information technology, and commercialize new ideas indicated by the output of patents and theoretical developments (Simmie, 2003). The E-LAUD framework will consider the complementary roles of knowledge-based capital to information technology and tools to support ecological sustainability through effective management and decision making processes (Fig. 3). Stakeholders require collaborative efforts for the management of changing landscapes in order to better accommodate urban ecological values.

Landscape ecological science has bottom up roles for valuation of ecological components through collaborative decision-making processes. For this, scientists from various disciplines need to cooperate, producing a common knowledge base capital including the tools and technologies that can be integrated into multifunctional actor-led landscape development. Such a knowledge framework expands the current pattern–process paradigm in landscape ecology, subsequently facilitating interdisciplinary research that is applicable in trans-disciplinary landscape development processes (Termorshuizen and Opdam, 2009). It is widely debated that the complex information about human influence on urban ecosystems, interdisciplinary and trans-disciplinary research involving natural and social sciences is imperative for a holistic approach to integrating ecology into the process of urban planning (Niemelä, 1999b). The integrated knowledge-based technology can then provide better outcomes for urban planning of ecological patterns and processes. For example, the prevalence of invasive exotic species in urban areas has been well managed within ecological knowledge management schemes and maintained the diversity of urban nature (Niemelä, 1999b).

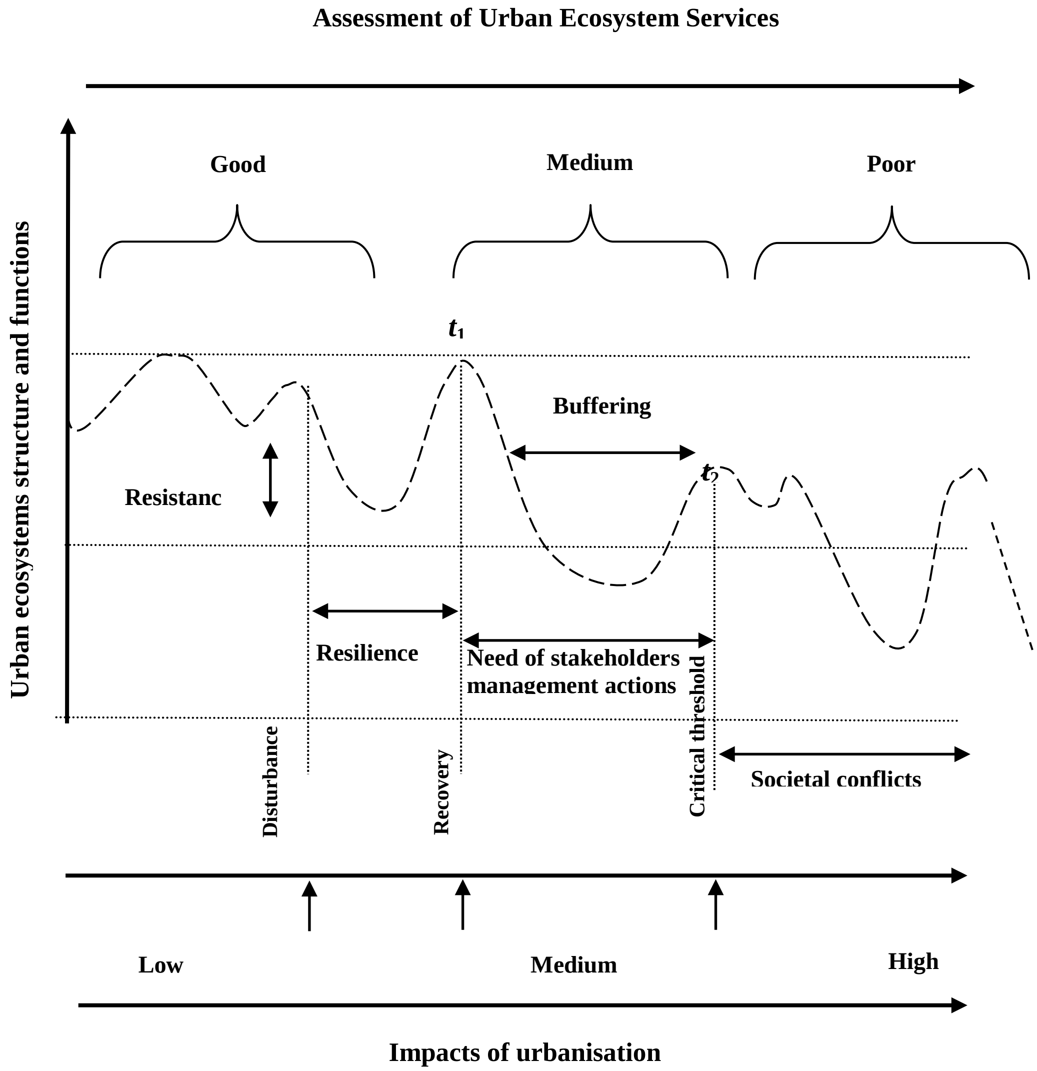

Fig 4. Ecological resilience of urban ecosystems and assessment of ecosystem services across the impact gradients (low, medium and high) of urbanisation. When urbanization increases, activities such as land use and land cover change patterns, building, infrastructure developments and soil and water pollution increases. In contrast, natural habitats for terrestrial and aquatic wildlife decreases followed by loss of ecosystem structure and functions. The system is resistant, and also able to absorb disturbances at this time. The system moves until the threshold point (t_1), where the system is in recovery phase. After this point, the natural vegetation becomes degraded, habitats become fragmented, water quality would become reduced and the overall performance of ecological services would gradually decline from good to medium. In some cases, buffering of ecosystem would stabilize the system. However, further human interventions would consequently lead the system to a condition beyond the threshold (t_2). Ecological response to urbanisation between t_1 and t_2 would be crucial. If the impacts of urbanisation are minimized at this phase, the system may return to normal. Interdisciplinary assessment and co-management of

urban ecosystems services by ecologists, urban planners, landscape architect, and urban residents together is significant at the buffering phase. However, passing this phase would bring the system into a different ecosystem regime with altered biological diversity and ecosystem structure and functions, which may have poor ecological performances and in many cases may result in increased conflicts in society (see Table 1 and Alberti and Marzluff, 2004; also see Tidal and Krasny, 2009).

5. Can E-LAUD framework be a basis for ecological resilience of urban ecosystems?

A truly resilient city has been regarded as a persistent entity, capable of withstanding an unforeseen shock which would alter or erase the identity of it. The urban ecosystem in a resilient city would reflect a sustainably planned design which explicitly account for the influence of both internal and external changes (Wu and Wu, 2011). Thus in some instances, urban ecosystems are classified as highly reliable and resilient ecosystems with high extraction of natural resources providing an invaluable source of goods and services both locally and globally (Bolund and Hunhammar, 1999). Interactions among social, economic, institutional and environmental factors, however, have transformed urban ecosystems as a part of complex systems, often characterised by dynamic, multiple thresholds, uncertainty and surprise (Cadenasso et al., 2006; Pickett et al., 2011). The alternative patterns of urban ecosystems have differential effects on ecological functions, for example, energy and material flows, nutrient dynamics and natural resources (Alberti and Marzluff, 2004). In some instances, urban ecosystems may be able to absorb disturbances if caused by one or a few external forces. However, if they are interrupted by multiple levels of threat, this can lead to non-linear dynamic responses, which are complex to understand (Holling, 2001). The complexity would usually occur due to increasing cross-scale interactions between spatial and temporal scales of social and biophysical effects, and an increasing connectivity of disturbances on patterns and processes (Cadenasso et al., 2006; Picket et al., 2008; Pickett et al., 2011). For instance, urban development imposes threats by altering the size and shape of green patches, disrupting wildlife inter-connectivity between ‘habitat islands’ and waterways and interrupting the supply of resources. Urban development also generates excessive nutrients and temperature changes which consequently affect biological diversity, altering reproduction and physiological adaptation of species (Grimm et al., 2008; Picket et al., 2008). The cumulative impacts of these activities become significant drivers of a ‘regime shift’, reducing ecological functioning and the resilience of urban ecosystem services (Fig. 4). Constant pressures on ecosystems further lead to loss of ecological resilience, and subsequently to a condition of ‘ecological collapse’, with minimal or no ecosystem services available to the society when passing beyond the threshold (Alberti and Marzluff, 2004). The ecological collapse creates crises in the society with conflicting demands placed on natural resources and increasingly poor public health. Table 1 explores the characteristics of key ecosystem services in resilient cities and cities functioning after the shift in ecological regime.

The E-LAUD framework has the potential to build the ecological resilience of urban ecosystems through integration of ecosystem functions with social and bio-physical dynamics, followed by urban spatial planning and design so as to avoid ecosystems passing beyond the threshold. The resilience of urban ecosystems can be improved through understanding the value of biodiversity, ecosystem structures and functioning, as well as ecosystem and human health (Fig. 3). Pickett et al. (2011) argued that for understanding the structure and function of urban ecosystems comprehensively, at least two basic frameworks are required. Firstly, the human ecosystem framework recognizes the relative significance of anthropogenic drivers of urban ecosystem structure and functions along space and time. Secondly, how the causes and drivers identified in the framework further interact to generate complex structure and functions of urban areas. The impacts of urban development, land use, human activities across the city, as well as natural climate variability and thresholds, and feedbacks of ecosystem changes are comprehensively investigated in the context of societal goods and services (Fig. 4). The E-LAUD framework places ecological resilience at the centre of adaptive management (co-managed by various actors, ecologists, urban designers, landscape architects, and urban residents) of the natural resources and strives to provide high priority goals for achieving potential ecosystem services (Fig. 3, also see Colding et al., 2006). The measures in environmental services, including the terrestrial and coastal food services, storm water filtration, water quality assessment, sediment capturing and storm barriers are all placed as significant components of adaptive management during urban planning (Fig. 4). The E-LAUD framework makes explicit consideration of trade-offs among all ecosystem services across the different scales of urban ecosystems (Halpern et al., 2008). Ecosystem trade-offs occur when the provision of ecosystem services varies (Rodriguez, 2006). Reduction of one ecosystem service may result in the increased use of other services. For example, higher demands on industrial produce may result in a lower supply of water. These trade-offs often arise from management choices of urban populations, which can change the type, magnitude, and relative mix of services provided by ecosystems. Explicit choices can have greater implications for management over various scales including temporal, spatial and reversible. In spatial scales the effects of trade-off are felt locally or at a distant location. In the temporal scale effects take place rapidly or slowly, and in the reversibility scale the effects may be back and forth in nature, but tend to return to the original state (Rodriguez, 2006).

The spatial nature of scales, such as fine or local scale patterns and processes, and broader or continental scale dynamics, are recognized as one of the significant urban ecosystem dynamics with spatio-heterogeniety, functional complexity and multiplicity functions (Alberti and Marzluff, 2004; Peters et al., 2008; Pickett et al., 2011). The E-LAUD framework (Fig. 3) forms the basis of adaptive management of urban ecosystems by understanding patterns and processes of urban ecology from local to continental or finer to broader scales, and by incorporating a range of measures to increase ecological resilience and ecosystem services in urban areas (Grimm et al., 2000; Rodriguez, 2006).

Table 1. Ecosystem services of cities with high ecological resilience vs cities following the regime shift.

Services	Resilient cities	Cities after regime shift
Aesthetic/cultural	Maintenance of architectural and natural heritages	Ruined heritages
Basic materials	Provision of food, water, fuel and shelter	Conflicting demands for resources
Health	Regulation of water purification, disease, soil and	Frequent outbreaks of

	flood	diseases
Democracy	Freedom of choice, decision making and mutual respect	Autocratic governments
Social security	Personal safety, advance warning of natural disasters	Increased crimes, natural disasters

6. Conclusions

Urban ecosystems are becoming an increasingly significant policy-relevant research focus given their interactions with society. Urban patterns influence the feasibility of using alternative systems to supply resources and services such as public transportation, energy, and drinking water to urban populations indirectly affecting their ecological impact. Human actions have significantly threatened sensitive species through preferentially destroying crucial habitats for urban development, while urban environments emerge as significant habitats for species with high dispersal ability and reproductive potential for surviving human related environmental changes. Here the complementary role of urban ecosystems that help build ecological resilience of the increasingly transforming urban landscapes is presented. We have focused on an exciting strategic frontier, the development of a complementary framework, combining Ecosystem, Land Use, Architecture and Urban Design (E-LAUD) in urban ecosystem management. It is argued that incorporating the E-LAUD framework in urban planning maximizes urban ecosystem services and builds ecological resilience. The E-LAUD framework forms the context of interdisciplinary and trans-disciplinary research among the components of urban planning and architecture including ecosystems, patch dynamics, waterways and urban wealth and innovation complementing wildlife habitats, biological conservation, filtering of pollutants and developing new tools and information technologies that help effective decision making processes in urban areas. However, a test of E-LAUD framework is crucial to achieve effective urban ecosystem management and promote ecological resilience. Such tests require strong adoption of guidelines and techniques. For example, the appropriate allocation of expertise for generating ecological and architectural data, project management and implementation, as well as making decisions through integrated actions from different stakeholders.

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Glossary

Ecology of city:

Ecology of city refers to how the city is viewed in the context of ecological change. For example, global environmental change is occurring at multiple scales. Material demands of production and human consumption are altering land use and cover, biodiversity, and hydrology on a local to regional scale, and urban waste discharge is affecting local to global biogeochemical cycles and climate. Grimm et al. (2008) argue that urban ecology integrates natural and social dimensions by radically altering environments from local to global scales, where cities are placed as important phenomena to present both problems and solutions to sustainability challenges facing during the 21st century. One of the best examples can be observed in Hong Kong, where rapid and accelerating changes are taking place in human civilisation and the biosphere. Ecology of City of Hong Kong by Boyden et al. (1981) provides a comprehensive insight into the links between human settlement and ecology.

Ecology in city:

Ecology in city refers to the perception of the city within the context of ecological change. For example, global environmental change has brought severe social and ecological unrest around the world. Following a natural disaster or conflict in cities, there can be social chaos or breakdown of order. The best examples are the breakdown of New Orleans following Hurricane Katrina, and Bagdad following the war in Iraq (Tidball and Krasny, 2009).

Ecological resilience:

Resilience in urban settings is the capacity of a city to persist without changing its basic structure, function and identity. Even if an unforeseen shock fundamentally alters or erases the identity of a city, the resilient city would withstand such impacts (Wu and Wu, 2011).

Habitat Island:

A Habitat Island (also see Island biogeography) is an isolated habitat created by urbanisation with considerable variations in size, and degrees of disturbance. City is a collection of 'habitat islands', where transformation of ‘natural’ habitats would continuously occur (Davis and Glick, 1978). Human actions influence rates of colonization and extinction of species across the ‘habitat islands’. Urbanization may bring a progressive decrease in species richness as a result of the reduced biogeographic functions of ‘habitat islands’, leading to biotic homogenization, a form of genetic, taxonomic or functional similarity amongst biota (Olden, 2006).

Island biogeography:

Island biogeography is a field of science studying the factors that affect species diversity and richness in isolated natural communities. Initially, this theory explained species richness of actual islands, while the concepts have also been tested in mountains surrounded by deserts, lakes surrounded by dry land, fragmented forests and even natural habitats surrounded by human-altered landscapes (MacArthur and Wilson, 1967).

Storm surge:

Storm surge is an offshore rise of water associated with a low pressure weather system. Storm surges are high winds pushing the water surfaces.

Urban Heat Island (UHI):

A metropolitan area which is significantly warmer than its surrounding rural areas due to human activities is usually referred as an Urban Heat Island or UHI (Arnfield, 2003).

List of Tables

Table 1. Ecosystem services of cities with high ecological resilience vs cities following the regime shift.

Services	Resilient cities	Cities after regime shift
Aesthetic/cultural	Maintenance of architectural and natural heritages	Ruined heritages
Basic materials	Provision of food, water, fuel and shelter	Conflicting demands for resources
Health	Regulation of water purification, disease, soil and flood	Frequent outbreaks of diseases
Democracy	Freedom of choice, decision making and mutual respect	Autocratic governments
Social security	Personal safety, advance warning of natural disasters	Increased crimes, natural disasters

List of Figures

Fig. 1. Distribution of species listed as threatened under the Environment Protection and Biodiversity Conservation in Australia.

Fig. 2. Per capita resource demand (Ecological Footprint) and resource supply (Bio-capacity) in Australia since 1961.

Fig. 3. A complementary framework for urban ecosystems based on Ecosystem-Land Use, Architecture and Urban Design (E-LAUD). The framework has overriding influences on ecological resilience between ecosystem health and human health. Designing landscape architecture for building, roads and railway network as well as constructing wetlands and reservoirs are significant parts of urban development. Mean time urban green patches, urban greenbelts, wetlands and estuaries all play an important role for urban ecologies by providing a refuge for urban wildlife as well as by filtering urban pollutants and defending storm surges. On the one hand, technological developments continue to influence the state of human health and on the other hand, the state of ecosystem health is largely determined by natural system maintained within the urban landscape. Ecological resilience is usually dependent on the magnitude of the status of both human health and ecosystem health. Urban wealth and knowledge will continue to help developing tools, infrastructure, technology and innovation and better management techniques for urban design and landscape planning as well as urban health and education. For instance, in the case of urban wetlands, design of effective stormwater filtering traps and better implementation can help promote ecosystem health; similarly, the exchange of knowledge through the use of geographic information system (GIS) amongst various stakeholders (resource managers v architects) can help effective decision making processes for urban resource managers on urban landscape management. However, in each case, either wetlands or green patches, the scale (finer versus broader or local versus spatial) can play a determining role on patterns and processes of urban ecologies. For example, resilience would vary individual or local to landscape or continental level green patches, while the response of broader scale (large in number) wetland/estuaries would be higher for stormwater surge filtering capacity than finer (small in number) scale wetlands (see also Pickett et al., 2009).

Fig. 4. Ecological resilience of urban ecosystems and assessment of ecosystem services across the impact gradients (low, medium and high) of urbanisation. When urbanization increases, activities such as land use and land cover change patterns, building, infrastructure developments and soil and water pollution increases. In contrast, natural habitats for terrestrial and aquatic wildlife decreases followed by loss of ecosystem structure and functions. The system is resistant, and also able to absorb disturbances at this time. The

system moves until the threshold point (t_1), where the system is in recovery phase. After this point, the natural vegetation becomes degraded, habitats become fragmented, water quality would become reduced and the overall performance of ecological services would gradually decline from good to medium. In some cases, buffering of ecosystem would stabilize the system. However, further human interventions would consequently lead the system to a condition beyond the threshold (t_2). Ecological response to urbanisation between t_1 and t_2 would be crucial. If the impacts of urbanisation are minimized at this phase, the system may return to normal. Interdisciplinary assessment and co-management of urban ecosystems services by ecologists, urban planners, landscape architect, and urban residents together is significant at the buffering phase. However, passing this phase would bring the system into a different ecosystem regime with altered biological diversity and ecosystem structure and functions, which may have poor ecological performances and in many cases may result in increased conflicts in society (see Table 1 and Alberti and Marzluff, 2004; also see Tidal and Krasny, 2009).

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