Landscape and Urban Planning 168 (2017) 22–30

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

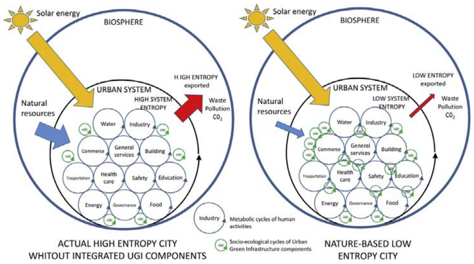
Perspective Essay

The low-entropy city: A thermodynamic approach to reconnect urban systems with nature

R. Pelorosso*, F. Gobattoni, A. Leone

DAFNE – Department of Agricultural and Forestry Sciences, University of Tuscia, Viterbo, Italy

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Urban green infrastructure
Urban ecosystem services
Urban sustainability
Urban planning
Circular economy
Low-entropy

ABSTRACT

Starting from the literature regarding the thermodynamics of open systems, the circular economy of Nature and complex socio-ecological systems, we propose a new boundary concept of a low-entropy city as the grounds on which to build actions and political strategies aimed at increasing urban sustainability.

A low-entropy city is defined as a responsive and conscious autopoietic human sociocultural niche that evolves and grows, enhancing its socio-ecological and structural complexity (reducing internal entropy) by adding and optimizing functional elements and synapses among those elements, while wastes (exported entropy to the biosphere) are minimized.

In particular, the low-entropy city concept is explored considering the role of Urban Green Infrastructure (UGI) in reducing city entropy. Following an analysis of the literature and applied research on UGI, the second law of thermodynamics and urban planning, a seminal nature-based planning strategy for low-entropy cities is presented. With appropriate adaptations, the strategy is applicable to all cities, despite the fact that urban systems can have different levels of UGI efficiency, different approaches to sustainability, and different demands for services as well as pressing environmental, social and economic issues. Some new entropy indicators are then presented, based on low-entropy city principles and two exemplificative urban evaluations based on these indicators are examined: urban storm water management and social degradation.

Finally, the low-entropy city concept and its implications in the urban sustainability debate are discussed, considering the possible difficulties that might be encountered when translating it into practice.

1. Introduction

Almost all known physical processes in the universe can be explained by thermodynamics (Ying, 2015), which is probably the most structured discipline for the study of complex systems (Bejan & Errera, 2016). Since the initial works on heat engines within closed and isolated systems, thermodynamic studies have evolved to investigate open systems which are far from equilibrium, such as ecosystems

---

* Corresponding author.
E-mail addresses: pelorosso@unitus.it (R. Pelorosso), f.gobattoni@unitus.it (F. Gobattoni), leone@unitus.it (A. Leone).

http://dx.doi.org/10.1016/j.landurbplan.2017.10.002
Received 14 March 2016; Received in revised form 17 August 2017; Accepted 3 October 2017

(Kondepudi & Prigogine, 2015). Many concepts developed in thermodynamics find applications in other fields, such as ecology and landscape ecology (Cushman, 2015; Gobattoni, Pelorosso, Lauro, Leone, & Monaco, 2011; Ho, 2013; Naveh, 1987), sociology (Mckinney, 2012), economy (Annila & Salthe, 2009; Georgescu-Roegen, 1971; Von Schilling & Straussfogel, 2008), circular economy (Ghisellini, Cialani, & Ulgiati, 2015), industrial ecology (Liao, Heijungs, & Huppes, 2012), organisational systems (Coldwell, 2016) and urban and landscape planning (Fistola & La Rocca, 2014; Leone, Gobattoni, & Pelorosso, 2016; Vandevyvere & Stremke, 2012). The Laws of Thermodynamics have also found applications in architecture and urban design (Braham, 2016; Vallero & Braiser, 2008): see for example the works of Philippe Rahm dealing with air flux dispersal and the consequent climatic and health conditions of buildings and urban parks (Scuderi & Rahm, 2014).

The First Law of Thermodynamics (FLT), also known as the conservation law, states that energy is always conserved across different states. The Second Law of Thermodynamics (SLT), or entropy law, states that during any process, useful energy, also defined as exergy or work capacity, is destroyed and entropy (disorder or waste) is produced. While the FLT focusses on the efficiency of energy transformations, the SLT looks at the direction in which processes are likely to proceed. Indeed, SLT quantifies the irreversibility of processes, providing us with an “arrow of time” of energy conversion and entropy production (Kleidon, 2009; Kondepudi & Prigogine, 2015). In particular, the SLT and the entropy principle provide a theoretical context which could help to a) clarify and unify a wide range of theories and studies, connecting them to fundamental principles of the evolution and functioning of Nature and b) define changes in human-provoked land use and their consequent biosphere alterations to reach the goal of long-term and solid sustainability (Leone et al., 2016).

Several urban planning and governance strategies have been developed to reach sustainability objectives giving social, economic and environmental aspects different weight. Moreover, several epistemologies and approaches have appeared in political and academic discourses with debates among different schools of thought, including, for example, critiques on urban metabolism and urban ecological studies (Bai, 2016; Golubiewski, 2012), and studies on the actual efficacy of proposed actions for the increase in urban sustainability (Premalatha, Tauseef, Abbasi, & Abbasi, 2014; Swyngedouw & Kaika, 2014). Another key point of the urban sustainability debate is the distinction between city and Nature. Following a widely accepted notion, a city is a complex ecosystem with strong human-dominated regulating and governing mechanisms that shape social and ecological processes (Bai, 2016). These mechanisms are partially explained by existing concepts, theories and approaches developed by ecological disciplines. On the other hand, several analogies between human-dominated and natural systems exist and indicators of natural ecosystems can help understand several processes within socio-economic systems such as cities (Bettencourt, 2013; Nielsen & Müller, 2009). Indeed, recognizing cities as part of Nature, i.e., as modified ecosystems, instead of mere human products, may impact the study of ecology in and of cities, and account for the metabolic footprint of urban areas on the whole biosphere (Pincetl, 2012). Finding a key to understanding both Nature and the nature of cities and linking them to global sustainability is therefore a challenge which will require the development of transdisciplinary integrative frameworks between different approaches (e.g. urban ecology and urban metabolism studies) and criteria (e.g. ecological, socio-economic and also architectural). At the same time, Nature in cities, also represented by so-called Urban Green Infrastructure (UGI), plays an important role in delivering a wide range of ecosystem services allowing improvements to quality of life and urban resilience (European Commission, 2013).

Despite numerous studies on thermodynamics, few papers present explicit spatial methods based on urban entropy aimed at supporting practical urban planning (Balocco & Grazzini, 2000; Filchakova, Robinson, & Scartezzini, 2007; Fistola & La Rocca, 2014). To our knowledge, only one work presents a spatial UGI planning based on thermodynamics, though it does not explicitly consider SLT (He, Shen, Miao, Dou, & Zhang, 2015).

In this essay, starting from the literature on the thermodynamics of open systems, we propose a new boundary concept of city (the low-entropy city) as the grounds on which to build actions and political strategies to increase urban sustainability. In particular, the role of UGI in reducing city entropy is explored and a new nature-based planning paradigm for low-entropy cities is presented. The paper is structured in sections: Section 2 illustrates the proposed concept of low-entropy city, while Section 3 describes UGI’s potential role within SLT. Section 4 then reports a first low-entropy strategy and new entropy indicators with the aim of operatively supporting UGI planning. Finally, we discuss the low-entropy city concept and its implications in the urban sustainability debate, considering possible difficulties which might be encountered when translating it into practice.

2. The low-entropy city concept

The Laws of Thermodynamics have been identified as the driving force of urban systems’ growth by several scholars with increasing consensus from the scientific world (Bristow & Kennedy, 2015; Gobattoni et al., 2011; Marull, Pino, Tello, & Cordobilla, 2010; Prigogine, 1997; Rees, 2012; Rees & Wackernagel, 1996). Furthermore, while economic growth has been correlated with urban development (Glaser, 2011), thermodynamics has been recognized as an essential driving force of economic growth theories (see Herrmann-Pillath, 2015). Indeed, every organism, population and ecosystem, cities included, can be seen as a thermodynamically open system, which grows and evolves, depending on its metabolism. Each system attempts to reduce the energy gradient applied to it, using all the available physical and chemical processes to consume free energy and the available physical and biological resources generated by the sun and photosynthetic activity (Isalgue, Coch, & Serra, 2007; Kleidon, 2010; Lin, 2015; Rees, 2012). Moreover, social cohesion has always been used to solve problems related to uncertainty and resource scarcity (Tanner et al., 2014). Social systems lead to higher complexity and quality levels by contributing to the overall level of system complexity, further channelling and managing energy fluxes (Fath, 2017). Thus, a city is characterised by a social complexity based on (real and digital) networks of people working for innovation and wealth creation, keeping the city from collapse and thermodynamic equilibrium. Urban growth appears therefore as an inevitable process, subjected to periods of crisis (e.g. shrinking phenomenon, see Haase, Haase, & Rink, 2014) and development, but a necessary and spontaneous evolutionary strategy of a technological society that builds its sociocultural niches and wants to satisfy its needs and optimize its energy consumption (Ellis, 2015).

Cities, like natural ecosystems, are self-organizing far-from-equilibrium dissipative structures because they grow and survive by continuously degrading and dissipating available energy and matter from the biosphere and sun (Prigogine, 1997; Rees, 2012). A City, like any other ecosystem, cannot be a self-sufficient system: it always requires matter and energy from outside the fuzzy urban limits while expelling products and waste to maintain levels of complexity, organization, and functionality (Fath, 2017). In order to persist over time and to evolve, a city should therefore be an autopoietic system, i.e. a system that maintains its identity and autonomy while remaining interactionally open to compensate for the inevitable losses due to the SLT with the help of external energy and material input (Pauliuk & Hertwich, 2015). However, while the ecosphere evolves and maintains itself by only feeding on an extra-terrestrial source of energy, and by continuously recycling matter, cities evolve by feeding on the limited natural resources in the rest of the biosphere and ejecting their wastes (e.g. pollution, heat, CO_2) back into it, often without reuse. Actual cities commonly require and employ high value energy (with a high exergy component, e.g. oil, gas) and release unsustainable, scarcely reusable, low value energy (entropy), which often constitutes an environmental problem and a cause of ecosystem alteration (Rockstrom et al., 2009).

There is therefore a need to build and transform today's cities into more sustainable urban systems with lower entropy release. Nature furnishes many examples of low-entropy systems where the use of resources is circular: nutrient, gas, water and energy cycles are closed whenever possible. Circular economy principles (i.e. recycling, reuse and recovery) are also derived from Nature and thermodynamics (Ghisellini et al., 2015). Recently, Ho (2013) has presented a theory of sustainable systems based on the circular thermodynamics of organisms. This theory suggests mimicking the processes and structures of natural systems in human activities to increase their resilience and to realize effective sustainable development. In general, these objectives can be reached by the following actions: a) the reduction of dissipative systems; b) the closure of cycles; c) the maximization of reciprocity, symbiosis, cooperative relationships, d) an increase in landscape diversity and complexity; e) the enhancement of energy and matter exchange.

Moreover, given the dependence of cities on the biosphere and external socio-ecological systems, the autopoietic capacity of low-entropy cities should also be based on a responsive and flexible interactive network of agents working to regain sovereignty over production, distribution and consumption patterns enabled through cooperative regional relationships which recognise overlapping and critical conditions (Lorrimar-Shanks & Owen, 2015). Indeed, direct relationships between producers and consumers of goods and services (e.g., energy, water and food) may reduce unsustainable exploitation and environmental concerns in source countries because consumers (cities) would be exposed to the impacts of production and transformation activities. At the same time, a conscious use of the resources and direct relationships between city and extra-urban territories could enhance the recognition of socio-economic and health consequences of city wastes even in remote regions and ecosystems. Such an autopoietic structure of responsive and conscious people networks, coupled with the functional internal socio-ecological and structural complexity suggested by Ho (2013), could then generate more adaptive and resilient complex social-ecological systems, i.e. cities able to face disturbances while retaining or rapidly returning to desired functions, structures, identities, and feedbacks, able to adapt to change, and to transform quickly systems that limit current or future adaptive capacity (Meerow, Newell, & Stults, 2016).

Thus, following the principles of the SLT togheter with those of the circular economy of Nature and complex socio-ecological systems, a low-entropy city is here defined as a responsive and conscious autopoietic human sociocultural niche that evolves and grows, enhancing its socio-ecological and structural complexity (reducing internal entropy) by adding and optimizing functional elements and synapses among those elements, while wastes (exported entropy to the biosphere) are minimized. Entropy exported to the biosphere is due to direct and indirect city wastes; the former deriving from urban metabolic cycles of socio-ecological and technical systems, the latter produced by unsustainable extraction of resources in source countries and ecosystems to uphold urban systems.

Several strategies can be employed to reduce urban entropy: the use of renewable and local energies, local food chains, investment in public transport and smart mobility, intelligent management systems for blocks of buildings, heat-cascades (i.e. the multi-stage reuse of residual thermal energy by temperature level), water reuse and so on. Many of these strategies have been proposed within the fields of industrial ecology, urban design, the planning of sustainable energy systems (see Stremke & Van den Dobbelsteen, 2013) or in practical applications of low-carbon, resilient, eco and smart cities. We hope that such strategies will merge in common, shared frameworks under the low-entropy city concept in future research developments.

In this paper, the role of urban green infrastructure planning in building low-entropy cities is explored.

3. Urban green infrastructure (UGI) and the second law of thermodynamics (SLT)

Many definitions of UGI are present in literature (Boyle et al., 2012; European Commission, 2013; Landscape Institute, 2013). In this paper, UGI is defined as an interconnected network of natural systems and Nature-Based Solutions (NBSs), localised at landscape scale and fully integrated with the built environment, which provides a diversified array of Urban Ecosystem Services (UESs) to the urban socio-ecological system increasing its resilience. NBSs are engineered green/ecological systems inspired or supported by, or copied from, Nature (EU, 2015). UESs are benefits that people derive directly or indirectly from natural and managed ecosystems (Gómez-Baggethun & Barton, 2013; Haase, Larondelle et al., 2014)

Following the SLT and low-entropy city view, UGI should allow urban systems to mimic natural ecosystem behaviour wherever possible.

Considering the city as our socio-cultural niche and artificial ecosystem, Man as an organism of that ecosystem which pursues the maximization of free energy use should limit the presence of unused city components and spaces. In a low-entropy city view, urban planners should aim to organize better city and land use by pursuing social-economic objectives employing all available and free forms of energy, defining the best employment for each urban space or, at least, the main green strategies for different urban zones.

Various types of urban space offer the opportunity to transform today's cities into low-entropy cities by imposing NBSs from a SLT view: two such typologies are unused and underused (green or grey) spaces, where the concept of unused/underused can be analysed both from a human and a SLT perspective. From a human perspective, unused/underused spaces do not provide the full range of socio-economic benefits that people expect from them. From a SLT perspective, such spaces neither make full use of available free energy and matter (e.g. solar energy, organic matter and water) nor activate nested and intertwined socio-ecological cycles among urban landscape components.

Unused and underused space typologies can be classified according to origin. They can be residual, vacant terrains of urban development (i.e. urban sprawl) or products of abandonment by industry or residents. Unused/underused spaces can include buildings, rooftops, walls, streets, squares and open areas in general and can therefore emerge in a strictly urban context or in a rural/urban fringe (e.g. metropolitan peripheries) or within/around industrial agglomerations. As a result, unused and underused spaces play a central role in debates about urbanisation models and city density (Nefs, 2006). Indeed, unused or underused spaces may hardly be accessible to the population, a source of city degradation, waste accumulation, a refuge for the homeless and undesired wild fauna, or places where criminal activity is poorly controlled. Moreover, unused/underused spaces may transform spontaneously into green/blue spaces by natural processes (e.g. water accumulation, nature colonization and ecological succession). Even though natural processes could increase green areas and the flux of UESs, such dynamics take a long time and the final or intermediate output may not be fully desirable for people (Rink & Thomas, 2016), or may even pose a risk to public health (Gulachenski, Ghersi, Lesen, & Blum, 2016).

Unused and underused urban spaces can clearly be seen as another thermodynamic waste of a SLT-blinded urban development. Moreover, present and planned green and blue areas in actual cities may supply a sub-optimal range of ecosystem services (Meerow & Newell, 2017) which could be improved by redesign projects following SLT. A UGI planned following the SLT would increase urban complexity, reducing both the city's internal entropy and its external entropy discharges (e.g. pollutants, floods, thermal radiation). Sunny walls can thus be seen as tree trunk bark, while a roof, a square or a residual non-urbanized lot can be equated to a forest clearing. Green roofs and walls, parks, trees, vegetated infiltration basins and so on, are thus engineered ecological

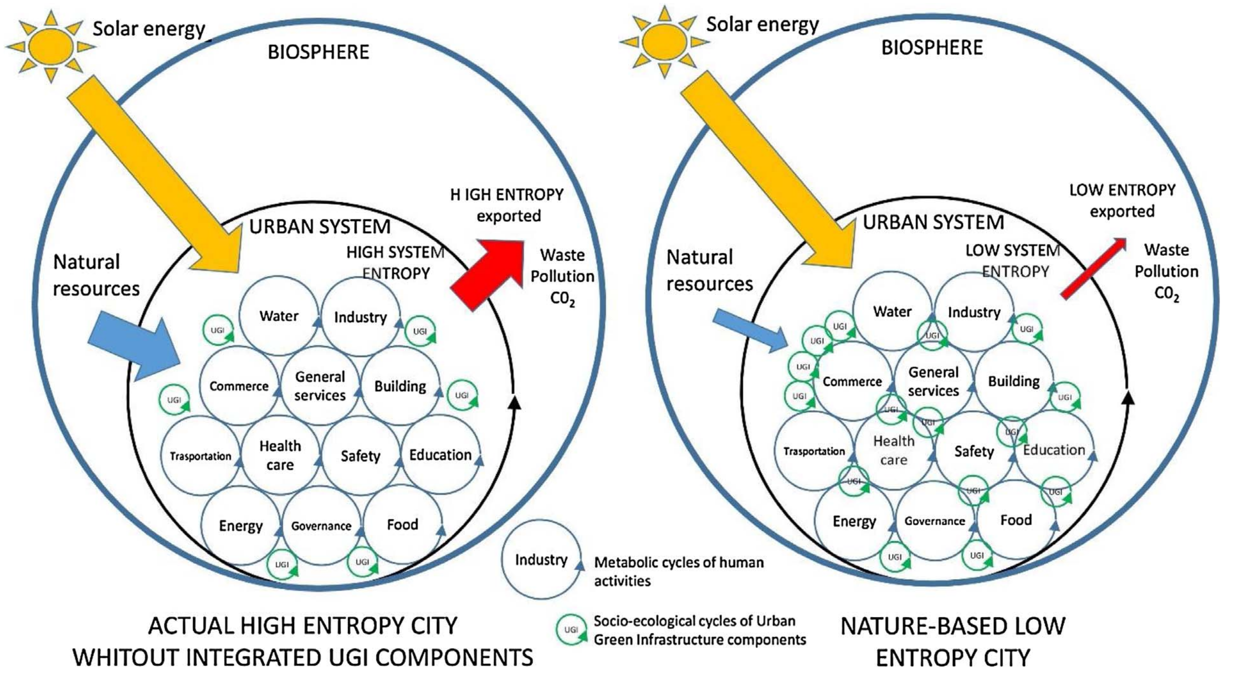


Fig. 1. Actual city without integrated UGI components compared with a theoretical nature-based low-entropy city with multifunctional UGI. The scheme has only a descriptive functionality of city metabolism and energy exchanges. Metabolic cycle dimensions are not related to their importance within the urban system. Socio-ecological cycles of UGI components are represented with smaller symbols with respect to human metabolic cycles in order to visualise the spatial organization and the mutual relations they could realize with the city subsystems in a SLT view.

systems providing several UESs (e.g. climate regulation) able both to use the incoming solar energy and rainfall, stocking it in biomass or in the soil layer, and to reduce the dispersion of entropy and low-value energy forms such as reflected radiation, radiant temperature or water runoff. Sustainable urban stormwater management techniques (e.g. SUDS, LID, BMPs) are examples of such NBSs (Fletcher et al., 2014). Increasing Nature in a city also enhances ecological connectivity within urban and extra-urban territories, a fundamental aspect for the health and resilience of the environment and biodiversity conservation (Pelorosso, Gobattoni, Geri, Monaco, & Leone, 2016). Moreover, the added UGI components could augment social capital, cohesion among citizens and institutions, a sense of place. They could even promote the creation of local networks, an essential prerequisite to realizing common and shared objectives of sustainability (Gobattoni, Pelorosso, Leone, & Ripa, 2015) and responsive and conscious autopoietic systems. In other words, by SLT-based UGI planning, a socio-ecological complexity could be realised that would allow a city to be more resilient and sustainable from a thermodynamic point of view, with several positive outcomes in both the social and the economic sectors. Fig. 1 shows a simplified scheme of the difference between an actual city without integrated UGI components, compared with a nature-based low-entropy city with multifunctional UGI. This scheme reports a conceptual synthesis of city behaviour in managing energy fluxes and releasing entropy when functional UGI components are added to the urban system. These functional UGI components have the capacity to capture unused energy and to reuse wastes (e.g. radiant heat, water, noise, pollution) coming from other human activities and to transform them into benefits for the population and other metabolic cycles. Social benefits (e.g. cultural ecosystem services) are also produced in the nature-based low entropy city by the improved health status of people and the creation of further relationships and networks among different system components leading to more sustainable processes, (eco) social and technological innovation. Consequently, functional UGI builds internal system complexity while reducing both the importation of external sources of energy (e.g. for cooling systems as well as for crime control) and the exportation/creation of entropy outside the urban system by direct and indirect wastes (e.g. pollution).

4. A strategy for planning UGI in low-entropy cities

In this section, we present a first planning strategy for building low-entropy cities by NBS. A low-entropy UGI planning strategy should aim to be as general and adaptable as possible in this seminal conceptual phase. We therefore decided to give only general indications, leaving further developments to future research. Indeed, our aim is to make the strategy applicable to any city, considering that each urban context needs tailored interventions based on local characteristics, multi-faced inertia and people-centered approaches with a systemic view in order to advance the city's sustainability level (Childers, Pickett, Grove, Ogden, & Whitmer, 2014; Krellenberg, Koch, & Kabisch, 2016). The strategy was thus developed bearing in mind the low-entropy city concept (Section 2), the role of UGI within the SLT (Section 3), and 8 basic planning concepts identified for low-entropy cities (Appendix A in the Supplementary material). The list of key planning concepts reported in Appendix A (Appendix A in the Supplementary material) provides not only the base on which the strategy is built but also a reference for further developments and improvements.

The strategy presented is constituted by the following phases: 1) assessment of available energy and matter fluxes; 2) assessment of UES supply and demand; 3) analysis of unused and underused spaces; 4) building of UGI scenarios; 5) impact evaluation of UGI scenarios; 6) definition of suitable planning and governance tools. Moreover, some new entropy indicators are proposed to evaluate NBSs following the low-entropy city concept.

When adopting this strategy, the assessment phases should have an explicit spatial character to guide practical decision-support within planning processes (Appendix A, planning concept 1, Spatial planning (in the Supplementary material)); they could also be supported by the adoption of modelling approaches (Appendix A, planning concept 2, Modelling (in the Supplementary material)). The UESs evaluation should be integrated as far as possible with the SLT view to avoid overlaps and increased assessment costs (Appendix A, planning concept

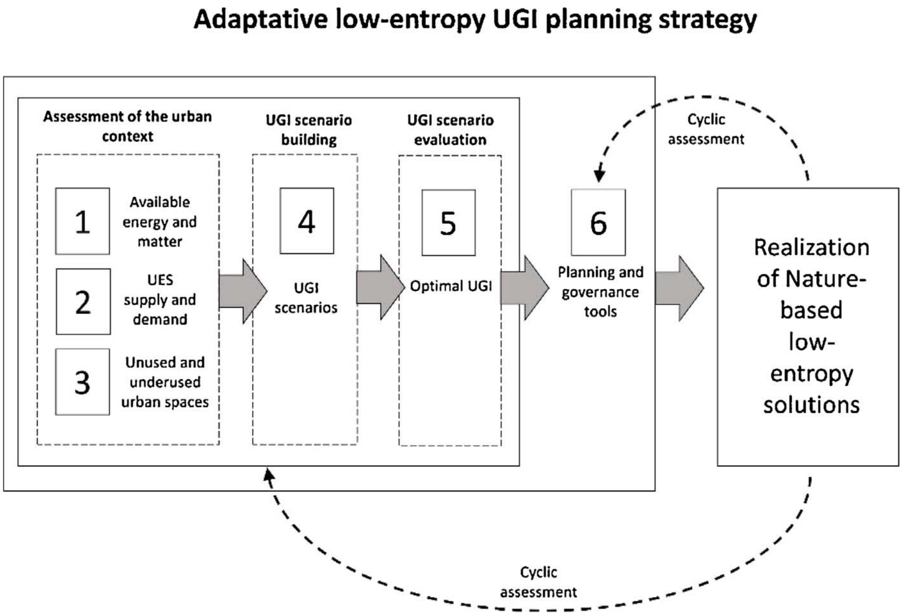


Fig. 2. Conceptual framework of the proposed adaptive low-entropy UGI planning strategy. Due to the flexible character of the strategy and the multiple relationships among the introduced low-entropy concepts and assessment methods, only the main connections among the six proposed phases are reported in the figure.

3, Urban Ecosystem Services (in the Supplementary material)). Unused and underused urban spaces can be classified using public participation, systemic survey and remote sensing approaches (Appendix A, planning concept 4, Unused and underused urban spaces (in the Supplementary material)). Stakeholders should be involved in all the phases following *ad hoc* procedures (Appendix A, planning concept 5, Social aspects (in the Supplementary material)). Moreover, a cyclic assessment phase should be performed to redefine the objectives, indicators and assessment methods of the strategy, following concepts of adaptive management and governance of complex socio-ecological systems (Appendix A, planning concept 6, Transferability and adaptability (in the Supplementary material)). Spatial Decision Support Systems (Appendix A, planning concept 7, Spatial Decision Support Systems (in the Supplementary material)) and Living labs (Appendix A, planning concept 8, Living labs (in the Supplementary material)) could constitute strategic tools for the implementation, dissemination and improvement of the proposed UGI planning strategy. The graphic overview provided in Fig. 2 represents the conceptual framework of the proposed adaptive strategy.

The strategy can be applied at different spatial and temporal scales from local to regional to biosphere level and from one time step to long time series simulations (Appendix A, planning concept 6, Transferability and adaptability (in the Supplementary material)). To be pragmatic and realistic, a lower level scale can substitute the biosphere scale even if the resulting applications and assessments are not strictly linked to theoretical assumptions. Design experiments should be monitored post-construction to study the benefits (i.e. UESs, system complexity) achieved at that specific location. In this view, local and small urban regeneration projects based on low-entropy principles could also prove valuable both in increasing city sustainability and in delivering information regarding how social-economic benefits can be obtained or maintained through an increase in socio-ecological urban complexity.

Table 1 reports a list of possible solutions adopted by traditional and nature-based low-entropy approaches for the main environmental, social and economic phenomena affecting urban systems. For each urban issue, NBSs are then shown to build low-entropy cities by enhanced UGI. It is worth noting that such NBSs must be correctly planned and that they are not simply alternatives to the current traditional approaches, rather they complement them. Indeed, a UGI planned to harness the power and sophistication of nature in a city can turn environmental, social and economic challenges into innovation opportunities, while also providing business opportunities (EU, 2015). However, such a nature-based UGI will entail an increased urban complexity that needs to be properly planned or at least driven in order to reduce costs and inefficiencies. The conversion of an empty lot into a park, for example, could furnish similar or preferable UESs to those offered by expensive and difficult to realize green roof projects. The same green strategy can be the best solution for one location, but completely negative for a similar location in another district or city. Definitely, in some cases densifying green areas could be discouraged, as in circumstances of urban gentrification, ecosystem disservices or high requirement of urban services and facilities (Antognelli & Vizzari, 2016; Wolch, Byrne, & Newell, 2014). A park, for example, cannot substitute certain urban services, such as those provided by a school, a theatre or a hospital. On the other hand, a green roof could augment the climatic condition of such buildings while also a small green area localised close to a school can help to spread wellness and educational values into the population. For each urban issue, Table 1 also reports the typology of UES provided by the proposed NBS and a selection of the best planning tools to realize such solutions.

Finally, some entropy indicators are suggested for each urban issue and nature-based solution (Table 2). The proposed indicators are intended to be easily employable by urban planners with the support of the modelling/assessment approaches used in the assessment phase of the planning strategy (Appendix A, planning concept 2, Modelling (in the Supplementary material)). Several indicators used in UES framework are here proposed within the low-entropy city strategy to integrate assessment methods avoiding overlaps and increased costs (Appendix A, planning concept 3, Urban Ecosystem Services (in the Supplementary material)). The proposed indicators, which also have an explicit spatial character (Appendix A, planning concept 1, Spatial planning (in the Supplementary material)), are classified in two groups: internal and external entropy indicators. The former aim to measure the internal urban system complexity obtained as a result of the proposed NBS. This internal complexity is then divided into ecological, social and structural/physical complexity. Internal entropy indicators can therefore help to measure UGI socio-ecological cycles within urban systems (see Fig. 1). The aim of external entropy indicators is to measure the impact of resource use within an urban system on external territories. Such territories can be localised within different scales depending on the chosen assessment strategy (e.g. biosphere or regional scale).

Clearly, many overlaps and feedbacks exist among the different urban issues, functions and services of NBSs. We argue that, according

Table 1
Environmental, social and economic phenomena, low-entropy nature-based solutions, urban ecosystem services and planning tools.

	Urban heat island	Urban storm water		Biodiversity loss	Sedentary and stressful jobs, traffic, pollution	Economic crisis, aging of buildings	Social degradation	Increased food necessity, overpopulation
Traditional approach	Air-conditioning	Grey infrastructures (e.g. pipes)	End-pipe treatment plants	Protected areas	gyms, hospitals, clinics	Urban architecture	Museums, exhibitions, libraries, schools	Supermarkets, fast foods
Low-entropy nature-based solutions	E.g. green roofs, tree plantations, parks	SUDS	phytoremediation plants, wetlands	Diffused green and blue areas	Blue and green areas	Blue and green areas	Blue and green areas	Urban gardens
Urban Ecosystem Services	Climate regulation	Water cycle regulation	Water treatment	Habitats for species	Recreation and education, mental and physical health, air quality regulation	Aesthetics, tourist and area value	Culture and education, sense of place	Provision of local food
Planning tools	Urban regeneration, UGI optimization plan, energy plan, urban master plan	Urban regeneration, UGI optimization plan, water management plan, urban master plan	Urban regeneration, UGI optimization plan, water management plan, urban master plan	Urban regeneration, UGI optimization plan, urban master plan	Urban regeneration, UGI optimization plan, urban master plan	Urban regeneration, UGI optimization plan, urban master plan	Urban regeneration, UGI optimization plan, urban master plan	Urban regeneration, UGI optimization plan, urban master plan

Table 2
Environmental, social and economic phenomena, low-entropy nature-based solutions and entropy indicators.

	Urban heat island	Urban storm water		Biodiversity loss	Sedentary and stressful jobs, traffic, pollution	Economic crisis, aging of buildings	Social degradation	Increased food necessity, overpopulation
Low-entropy nature-based solutions	green roofs, tree plantations, parks	SUDS	phytoremediation plants, wetlands	Diffused green and blue areas	Blue and green areas	Blue and green areas	Blue and green areas	Urban gardens
Internal entropy indicators								
Ecological complexity	n° of species, n° of trees, covered area	n° and typology of SUDS	n° and typology of species, local freshwater ecosystems health status	n° of species, n° of trees, covered area	n° of species, n° of trees. covered area	n° of species, n° of trees, covered area	n° of species, n° of trees, covered area	n° of species, n° of trees, covered area
Social complexity	People and enterprises involved	People and water enterprises	People and water enterprises	n° and typology of visitors and residents	n° and typology of visitors and residents	n° and typology of residents and tourists, enterprises involved	n° and typology of visitors and residents, n° of crimes	People and enterprises involved
Structural/physical complexity	Internal or local T variation	% infiltration or stored water	Re-used water	spatial distribution of land uses	spatial distribution of land uses, local air quality variation	spatial distribution of land uses	spatial distribution of land uses	spatial distribution of urban gardens
External entropy indicators								
Biosphere/regional complexity	Urban heat island, energy cost, CO_2 emission	Outlet flooding, global runoff	Health status of receiving freshwater and sea ecosystems, CO_2 emission	Landscape connectivity	Extra-urban trips, CO_2 emission, regional health system cost	Geographic distribution of visitors	Socio-ecological issues in countries and ecosystems related with unresponsive and unconscious city resource consumption	Imported food, CO_2 emission

to the SLT approach environmental, social and economic aspects are strictly intertwined. A holistic and transdisciplinary UGI assessment (considering economic aspects such as Life Cycle Assessment and social aspects such as acceptability to citizens) will therefore lead to a more effective evaluation of low-entropy strategies.

To clarify the use of the proposed indicators, two examples of nature-based low-entropy evaluations tackling two different urban issues are presented: the management of storm water and social degradation.

The aim of urban storm water management is to reduce urban runoff and pollution dispersal. A low-entropy approach suggests the use of diffuse Sustainable Urban Drainage Systems (SUDSs) as NBSs to couple with the traditional approach based on grey infrastructure. SUDSs (e.g. green roofs, rain gardens, infiltration basins) allow storm water to be infiltrated, stocked and used locally, thus reducing the load on the grey infrastructures. Instead this load might be not correctly managed by traditional systems, and would thus be released as waste into the environment, leading to health problems and increased entropy outside the urban system. Following the proposed strategy, after an analysis of water fluxes within the urban system, SUDS scenarios should be realised where water fluxes are not correctly managed by the current grey system. We could also evaluate these scenarios in terms of internal and external entropy indicators. Among the former we would include SUDS typology (presence of plant species that increase the ecological complexity of the city), the number of new water management enterprises (increased social complexity defined as a network of people involved in metabolic cycles aimed at managing energy and material fluxes sustainably) and the evaluation of water infiltrated or stored locally (physical complexity). The latter index gives a measure of the alternative (nature-based) water fluxes realised within the urban system with respect to the artificial water behaviours realised in conditions of high imperviousness. The runoff at the outlet of an urban catchment can be related to the reduction in entropy released from the urban system after SUDS scenario implementation (regional complexity).

Social degradation, on the other hand, is a phenomenon that affects the history, culture and traditions of a community (i.e. its social capital) which are at the basis of social evolution and self-organization. High levels of social degradation therefore hamper people's attempts to coordinate their activities with the aim of achieving mutual benefits (Gobattoni et al., 2015). Examples of social degradation are found in deprived districts, the neglected or abandoned areas where criminality, inequalities, social exclusion, marginalisation and poverty have a serious impact on human health, quality of life, well-being and the security of citizens, particularly among the less privileged social classes. The suggested entropy indicators can be used to evaluate the efficiency of an urban park to regenerate such urban areas in terms of SLT. Increased internal ecological complexity can be measured by the number of species or trees in a green area, while the social complexity of an urban system can be evaluated by looking at the measured or expected variation in residents or crimes around the urban park. Such indicators are related to life quality and the possibility of creating positive and safe social relationships among residents. Structural/physical complexity could be investigated by the variation in land use pattern due to the park's realisation and the consequent changes in urban services and forms. The relationship between urban land use patterns and the efficient use of resources has been identified for energy consumption and carbon emissions (Ye et al., 2015) and social capital (Bramley & Power, 2009; Nassauer & Raskin,2014). Finally, the cultural impact of the park on the sustainability of the autopoietic urban system can be assessed by investigating people's awareness of socio-ecological issues in countries and ecosystems related with unresponsive and unconscious city resource consumption. The educational values of the park, also associated with the planning and design processes, can be thus evaluated by questionnaires.

5. Discussion

The proposed low entropy UGI planning strategy still presents some limitations in its preliminary general form and it might encounter some obstacles when translated into practice.

A limit of the current strategy is the difficulty of taking into account social aspects exhaustively. The low-entropy city concept recalls for conscious and responsible people networks to reach a more equitable and fair use of resources. The derived strategy provides room for social assessment, through embedded stakeholder involvement in every phase. It also contains some specific indicators (see Table 2) designed to measure a number of social benefits of proposed NBSs and to consider socio-ecological issues related to different people needs and the unresponsive and unconscious city resource consumption. However, the complex, cause-effect relationships underlying social phenomena are hard to predict. Therefore, a correct definition of sustainable actions requires a specific investigation into the social changes which can derive from, or be activated by, interventions on the urban system, and which could generate unequal and unjust social and environmental conditions (Appendix A, planning concept 5, Social aspects (in the Supplementary material)). Future research will aim to examine in depth and, where possible, improve the proposed approach especially as regards social implications, which can vary greatly and are hard to represent by means of one-fits-all indicators. The contribution from Urban Political Ecology (Heynen, Kaika, & Swyngedouw, 2006) to this end would surely be pivotal in completing the vision provided by the low-entropy concept through the comprehension and in-depth perception of the social, economic, political processes behind highly uneven urban landscapes.

Other constraints affecting the proposed nature-based low entropy city strategy may be related to the management of complexity. The low-entropy approach considers the city as a complex socio-ecological system and the strategy and indicators derived are designed to assess the multiple and intertwined urban processes behind this complexity. Translating complexity into urban planning practice is a crucial issue that generates increased costs, new rules of governance and stakeholder involvement, which all deserve to be accurately studied (Floyd, Iaquinto, Ison, & Collins, 2014; Richardson, 2016).

An essential prerequisite for successful implementations of the proposed planning strategy is an adequate knowledge and understanding of the main concepts at the basis of the approach, on the part of managers, administrators and planners. If correctly informed and fully engaged, they could put the low-entropy city concept into practice using planning tools which are already available, or possibly pave the way to new special regulations and technical rules favouring the achievement (and the measurement) of quantitative results in terms of entropy reduction. Furthermore, the political context in which the strategy is pursued plays a key role, since the final outcomes of any general UGI and NBS strategy strictly depends on the willingness and engagement of local institutions (Haase et al., 2017; Krellenberg et al., 2016). As for other planning strategies towards city sustainability (Buijs et al., 2016; Krellenberg et al., 2016), the active involvement of city dwellers and their conscious acceptance are fundamental elements of a successful low-entropy strategy implementation. Although the strategy envisages stakeholder involvement in all the phases, specific procedures are required to ensure the engagement of city dwellers. An adequate set of *ad hoc* measures to increase the stakeholders' awareness of urban sustainability issues, and to enable them to transfer that knowledge into action, could be identified by making use of the boundary work framework, defined by Cash et al. (2003) and regarding which the scientific literature reports interesting applications (e.g. Adem Esmail & Geneletti, 2017). These measures, primarily aimed at mediating tension among involved stakeholders, could enable the practical realisation of interventions conceived according to the low-entropy view.

Moreover, the reported general low-entropy UGI planning strategy needs to be transferred and adapted to the specific local characteristics of the urban context in which it is to be applied, thus requiring an initial effort to analyse the city system and, subsequently, to identify appropriate measures to reduce entropy production. This preliminary evaluation can be time-consuming and it requires economic resources and multiple specific expertise. Thus, the low entropy approach can meet opposition from administrators and it can be seen as hard to realize, above all in certain urban contexts with unfavourable socio-economic conditions. Future research and studies should be then addressed to the further development of the operative low-entropy strategy definition working on improving the structure and description of each phase. Additional efforts should be directed to test the proposed entropy indicators and possibly to extend the list of indicators to cover other environmental, social and economic phenomena.

Finally, practical implementations on exemplificative study cases or the creation of *ad hoc* urban living labs, would provide useful information and datasets not only to quantify the contribution of the proposed approach in terms of socio-environmental impact reduction, but also to improve and detail the general low-entropy strategy and indicators discussed here. Indeed, these intertwined complexity-related issues and the effectiveness of the possible low-entropy solutions can be evaluated only by real study cases. An initial research (and economic) effort is therefore necessary to realize front-runner low-entropy implementations to real urban areas in order to define effective UGI planning strategies.

6. Conclusions

In today's context of climate change and natural resource scarcity, we need to accelerate the race towards city sustainability. However, we must not only select with care the proper direction for future city development, but also find strong grounds on which to base our moves to avoid expensive and/or late re-thinking. A correct and holistic view of cities within the natural world could help better define strategies to solve human conflicts with the natural environment. In this view, the low-entropy city is a boundary concept that allows a unique and holistic vision of human-nature connections (Ives et al., 2017), able to confer conceptual synthesis to the multiple frameworks characterizing urban ecology along the path towards a Science of Cities (McPhearson et al., 2016).

The Laws of Thermodynamics establish that a zero waste growth is impossible to obtain, therefore the proposed low-entropy city represents a feasible goal towards which all present or future cities should aspire. In this essay, we present a low-entropy strategy for UGI planning. Further research efforts will aim to improve the strategy but also to transfer the low-entropy concept into different application fields and geographical contexts, going beyond the implementation of UGI in urban areas. Indeed, the wide applicability of this concept could allow its implementation in a variety of urban contexts, sub-systems (e.g. water, waste, health, and transport sectors), landscapes (e.g. energy landscapes) and innovative sustainability assessment procedures.

In this paper, we propose our (still theoretical but potentially operative) low-entropy planning strategy and indicators designed to tackle several environmental, social and economic urban issues by means of Nature-based solutions. We are aware that the proposed low-entropy approach is perfectible and several awkward points for its applicability as well as suggestions for future researches have been reported. Nonetheless, we think that like other approaches to sustainability, the low entropy concept will only have real effectiveness when the cultural evolution of society is sustained by proper levels of complexity, organization and functionality (Costanza, 2013; Fath, 2017; Pirsig, 1991) able to accept the low entropy paradigm as a whole, thus avoiding misleading and erroneous applications generating unexpected consequences at different temporal and spatial scales.

However, we hope that our nature-based view of urban systems will stimulate urban planners, urban ecologists, architects and scientists, and inspire theoretical discussions as well as practical follow-ups that will contribute to realize even more low-entropy human systems.

Acknowledgements

The authors would like to thank the anonymous reviewers for their guidance. Raffaele Pelorosso and Federica Gobattoni would like to thank Matilde for her support in opening their minds towards new research challenges.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landurbplan.2017.10.002.

References

Adem Esmail, B., & Geneletti, D. (2017). Design and impact assessment of watershed investments: an approach based on ecosystem services and boundary work. *Environmental Impact Assessment Review, 62*, 1–13. http://dx.doi.org/10.1016/j.eiar.2016.08.001.

Annila, A., & Salthe, S. (2009). Economies evolve by energy dispersal. *Entropy, 11*(4), 606–633. http://dx.doi.org/10.3390/e11040606.

Antognelli, S., & Vizzari, M. (2016). Ecosystem and urban services for landscape liveability: A model for quantification of stakeholders' perceived importance. *Land Use Policy, 50*(JANUARY), 277–292. http://dx.doi.org/10.1016/j.landusepol.2015.09.023.

Bai, X. (2016). Eight energy and material flow characteristics of urban ecosystems. *Ambio, 45*(7), 819–830. http://dx.doi.org/10.1007/s13280-016-0785-6.

Balocco, C., & Grazzini, G. (2000). Thermodynamic parameters for energy sustainability of urban areas. *Solar Energy, 69*(4), 351–356. http://dx.doi.org/10.1016/S0038-092X(00)00069-4.

Bejan, A., & Errera, M. R. (2016). Complexity, organization, evolution, and constructal law. *Journal of Applied Physics, 119*(7), http://dx.doi.org/10.1063/1.4941554.

Bettencourt, L. M. A. (2013). The origins of scaling in cities. *Science, 340*, 1438–1441. http://dx.doi.org/10.1126/science.1235823.

Boyle, C., Gamage, G., Fassman, E., Knight-Lenihan, S., Schwendenmann, L., & Thresher, W. (2012). *Greening cities: a review of green infrastructure.* University of Auckland.

Braham, W. W. (2016). *Architecture and Systems Ecology Thermodynamics principles of environmental building design, in three parts.* Routledge.

Bramley, G., & Power, S. (2009). Urban form and social sustainability: The role of density and housing type. *Environment and Planning B: Planning and Design, 36*(1), 30–48. http://dx.doi.org/10.1068/b33129.

Bristow, D., & Kennedy, C. (2015). Why do cities grow? Insights from nonequilibrium thermodynamics at the urban and global scales. *Journal of Industrial Ecology, 19*(2), 211–221. http://dx.doi.org/10.1111/jiec.12239.

Buijs, A. E., Mattijssen, T. J., Van der Jagt, A. P., Ambrose-Oji, B., Andersson, E., Elands, B. H., & Steen Møller, M. (2016). Active citizenship for urban green infrastructure: fostering the diversity and dynamics of citizen contributions through mosaic governance. *Current Opinion in Environmental Sustainability, 22*(June 2016), 1–6. http://dx.doi.org/10.1016/j.cosust.2017.01.002.

Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., ... Mitchell, R. B. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America, 100*(14), 8086–8091. http://dx.doi.org/10.1073/pnas.1231332100.

Childers, D. L., Pickett, S. T. A., Grove, J. M., Ogden, L., & Whitmer, A. (2014). Advancing urban sustainability theory and action: Challenges and opportunities. *Landscape and Urban Planning, 125*, 320–328. http://dx.doi.org/10.1016/j.landurbplan.2014.01.022.

Coldwell, D. (2016). Entropic citizenship behavior and sustainability in urban organizations: Towards a theoretical model. *Entropy, 18*(12), http://dx.doi.org/10.3390/e18120453.

Costanza, R. (2013). A theory of socio-ecological system change. *Journal of Bioeconomics, 16*(1), 39–44. http://dx.doi.org/10.1007/s10818-013-9165-5.

Cushman, S. A. (2015). Thermodynamics in landscape ecology: The importance of integrating measurement and modeling of landscape entropy. *Landscape Ecology, 30*(1), 7–10. http://dx.doi.org/10.1007/s10980-014-0108-x.

EU (2015). *Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities.* http://dx.doi.org/10.2777/765301.

Ellis, E. C. (2015). Ecology in an anthropogenic biosphere. *Ecological Monographs, 85*(3), 287–331. http://dx.doi.org/10.1890/14-2274.1.

European Commission. (2013). *Green Infrastructure (GI) – Enhancing Europe's Natural Capital. Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions, Brussels, 6.5.2013COM(2013) 249 final.*

Fath, B. D. (2017). System ecology, energy networks, and path to sustainability. *International Journal of Design & Nature and Ecodynamics, 12*(1), 1–15. http://dx.doi.org/10.2495/DNE-V12-N1-1-15.

Filchakova, N., Robinson, D., & Scartezzini, J. L. (2007). Quo vadis thermodynamics and the city: A critical review of applications of thermodynamic methods to urban systems. *International Journal of Ecodynamics, 2*(4), 222–230. http://dx.doi.org/10.2495/ECO-V2-N4-222-230.

Fistola, R., & La Rocca, R. A. (2014). *The Sustainable City and the Smart City: measuring urban entropy first. The sustainable city IX*. WIT Presshttp://dx.doi.org/10.2495/sc140451 [p. 537].

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., ... Viklander, M. (2014). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal,* 1–18. http://dx.doi.org/10.1080/1573062X.2014.916314.

Floyd, J., Iaquinto, B. L., Ison, R., & Collins, K. (2014). Managing complexity in Australian urban water governance: Transitioning Sydney to a water sensitive city. *Futures, 61*, 1–12. http://dx.doi.org/10.1016/j.futures.2014.04.002.

Gómez-Baggethun, E., & Barton, D. N. (2013). Classifying and valuing ecosystem services for urban planning. *Ecological Economics, 86*, 235–245. http://dx.doi.org/10.1016/j.ecolecon.2012.08.019.

Georgescu-Roegen, N. (1971). *The entropy law and the economic process.* Harvard Univ. Press.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2015). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*. http://dx.doi.org/10.1016/j.jclepro.2015.09.007.

Glaser, E. (2011). *Triumph of the city. How our greatest invention makes us richer, smarter, greener, healthier and happier.* New York: The Pinguin presshttp://dx.doi.org/10.1017/CBO9781107415324.004.

Gobattoni, F., Pelorosso, R., Lauro, G., Leone, A., & Monaco, R. (2011). A procedure for mathematical analysis of landscape evolution and equilibrium scenarios assessment. *Landscape and Urban Planning, 103*(3–4), 289–302. http://dx.doi.org/10.1016/j.landurbplan.2011.08.011.

Gobattoni, F., Pelorosso, R., Leone, A., & Ripa, M. N. (2015). Sustainable rural development: The role of traditional activities in Central Italy. *Land Use Policy, 48*, 412–427. http://dx.doi.org/10.1016/j.landusepol.2015.06.013.

Golubiewski, N. (2012). Is there a metabolism of an urban ecosystem? An ecological critique. *Ambio, 41*(7), 751–764. http://dx.doi.org/10.1007/s13280-011-0232-7.

Gulachenski, A., Ghersi, B. M., Lesen, A. E., & Blum, M. J. (2016). Abandonment, ecological assembly and public health risks in counter-urbanizing cities. *Sustainability (Switzerland), 8*(5), 1–26. http://dx.doi.org/10.3390/su8050491.

Haase, D., Kabisch, S., Haase, A., Andersson, E., Banzhaf, E., Baró, F., ... Wolff, M. (2017). Greening cities – To be socially inclusive? About the alleged paradox of society and ecology in cities. *Habitat International, 64*, 41–48. http://dx.doi.org/10.1016/j.habitatint.2017.04.005.

Haase, D., Haase, A., & Rink, D. (2014). Conceptualizing the nexus between urban shrinkage and ecosystem services. *Landscape and Urban Planning, 132*, 159–169. http://dx.doi.org/10.1016/j.landurbplan.2014.09.003.

Haase, D., Larondelle, N., Andersson, E., Artmann, M., Borgström, S., Breuste, J., ... Elmqvist, T. (2014). A quantitative review of urban ecosystem service assessments: Concepts, models, and implementation. *Ambio, 43*(4), 413–433. http://dx.doi.org/10.1007/s13280-014-0504-0.

He, X., Shen, S., Miao, S., Dou, J., & Zhang, Y. (2015). Quantitative detection of urban climate resources and the establishment of an urban climate map (UCMap) system in Beijing. *Building and Environment, 92*, 668–678. http://dx.doi.org/10.1016/j.buildenv.2015.05.044.

Herrmann-Pillath, C. (2015). Energy, growth, and evolution: Towards a naturalistic ontology of economics. *Ecological Economics*. http://dx.doi.org/10.1016/j.ecolecon.2014.11.014.

Heynen, N., Kaika, M., & Swyngedouw, E. (2006). In the nature of cities: Urban political ecology and the politics of urban metabolism. *Urban Geography, 28*. http://dx.doi.org/10.2747/0272-3638.28.2.206.

Ho, M.-W. (2013). Circular thermodynamics of organisms and sustainable systems. *Systems, 1*(3), 30–49. http://dx.doi.org/10.3390/systems1030030.

Isalgue, A., Coch, H., & Serra, R. (2007). Scaling laws and the modern city. *Physica A: Statistical Mechanics and Its Applications, 382*(2), 643–649. http://dx.doi.org/10.1016/j.physa.2007.04.019.

Ives, C. D., Giusti, M., Fischer, J., Abson, D. J., Klaniecki, K., Dorninger, C., ... von Wehrden, H. (2017). Human-nature connection: A multidisciplinary review. *Current Opinion in Environmental Sustainability, 26–27*, 106–113. http://dx.doi.org/10.1016/j.cosust.2017.05.005.

Kleidon, A. (2009). Nonequilibrium thermodynamics and maximum entropy production in the Earth system: applications and implications. *Die Naturwissenschaften, 96*(6), 653–677. http://dx.doi.org/10.1007/s00114-009-0509-x.

Kleidon, A. (2010). Life, hierarchy, and the thermodynamic machinery of planet Earth. *Physics of Life Reviews, 7*(4), 424–460. http://dx.doi.org/10.1016/j.plrev.2010.10.002.

Kondepudi, D., & Prigogine, I. (2015). *Modern thermodynamics: From heat engines to dissipative structures.* John Wiley & Sons, Ltdhttp://dx.doi.org/10.1016/j.pnsc.2008.07.002.

Krellenberg, K., Koch, F., & Kabisch, S. (2016). Urban Sustainability Transformations in lights of resource efficiency and resilient city concepts. *Current Opinion in Environmental Sustainability, 22*, 51–56. http://dx.doi.org/10.1016/j.cosust.2017.04.001.

Landscape Institute (2013). *Green infrastructure. An integrated approach to land use*.

Leone, A., Gobattoni, F., & Pelorosso, R. (2016). Energy supply, thermodynamics and territorial processes as a new paradigm of sustainability in planning science and practice. In R. Papa, & R. Fistola (Eds.). *Smart energy in the smart city. Urban planning for a sustainable future* (pp. 83–101). Berlin: Springer International Publishing.

Liao, W., Heijungs, R., & Huppes, G. (2012). Thermodynamic analysis of human-environment systems: A review focused on industrial ecology. *Ecological Modelling, 228*, 76–88. http://dx.doi.org/10.1016/j.ecolmodel.2012.01.004.

Lin, H. (2015). Thermodynamic entropy fluxes reflect ecosystem characteristics and succession. *Ecological Modelling, 298*, 75–86. http://dx.doi.org/10.1016/j.ecolmodel.2014.10.024.

Lorrimar-Shanks, J., & Owen, C. (2015). A critical approach to ecological urbanism in Hong Kong. *International Journal of Urban Sustainable Development, 3138*(September), 1–16. http://dx.doi.org/10.1080/19463138.2015.1083436.

Marull, J., Pino, J., Tello, E., & Cordobilla, M. J. (2010). Social metabolism, landscape change and land-use planning in the Barcelona Metropolitan Region. *Land Use Policy, 27*(2), 497–510. http://dx.doi.org/10.1016/j.landusepol.2009.07.004.

McPhearson, T., Pickett, S. T. A., Grimm, N. B., Niemel, J., Alberti, M., ... Elmqvist, T., ... Qureshi, S. (2016). Advancing urban ecology toward a science of cities. *Bioscience, 66*(3), 198–212. http://dx.doi.org/10.1093/biosci/biw002.

Mckinney, L. A. (2012). Entropic disorder: New frontiers in environmental sociology. *Sociological Perspectives, 55*(2), 295–317. http://dx.doi.org/10.1525/sop.2012.55.2.295.296.

Meerow, S., & Newell, J. P. (2017). Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit. *Landscape and Urban Planning, 159*, 62–75. http://dx.doi.org/10.1016/j.landurbplan.2016.10.005.

Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning, 147*, 38–49. http://dx.doi.org/10.1016/j.landurbplan.2015.11.011.

Nassauer, J. I., & Raskin, J. (2014). Urban vacancy and land use legacies: A frontier for urban ecological research, design, and planning. *Landscape and Urban Planning, 125*, 245–253. http://dx.doi.org/10.1016/j.landurbplan.2013.10.008.

Naveh, Z. (1987). Biocybernetic and thermodynamic perspectives of landscape functions and land use patterns. *Landscape Ecology, 1*(2), 75–83. http://dx.doi.org/10.1007/BF00156229.

Nefs, M. (2006). Unused urban space: conservation or transformation? Polemics about the future of urban wastelands and abandoned buildings. *City & Time, 2*(1), 47–58.

Nielsen, S. N., & Müller, F. (2009). Understanding the functional principles of nature–Proposing another type of ecosystem services. *Ecological Modelling, 220*(16), 1913–1925. http://dx.doi.org/10.1016/j.ecolmodel.2009.04.022.

Pauliuk, S., & Hertwich, E. G. (2015). Socioeconomic metabolism as paradigm for studying the biophysical basis of human societies. *Ecological Economics, 119*, 83–93. http://dx.doi.org/10.1016/j.ecolecon.2015.08.012.

Pelorosso, R., Gobattoni, F., Geri, F., Monaco, R., & Leone, A. (2016). Evaluation of Ecosystem Services related to Bio-Energy Landscape Connectivity (BELC) for land use decision making across different planning scales. *Ecological Indicators, 61*, 114–129. http://dx.doi.org/10.1016/j.ecolind.2015.01.016.

Pincetl, S. (2012). Nature, urban development and sustainability – What new elements are needed for a more comprehensive understanding? *Cities, 29*, S32–S37. http://dx.doi.org/10.1016/j.cities.2012.06.009.

Pirsig, R. M. (1991). *Lila: an inquiry into morals.* New York, NY: Bantam Books.

Premalatha, M., Tauseef, S. M., Abbasi, T., & Abbasi, S. A. (2014). The promise and the performance of the world's first two zero carbon eco-cities. *Energy Education Science and Technology Part B: Social and Educational Studies, 6*(1), 81–96. http://dx.doi.org/10.1016/j.rser.2013.05.011.

Prigogine, I. (1997). *The end of certainty: time, chaos and the new laws of nature.* New York: The Freee Press.

Rees, W., & Wackernagel, M. (1996). Urban ecological footprints: why the cities cannot be sustainable – And why they are a key to sustainability. *Environmental Impact Assessment Review, 16*, 223–248.

Rees, W. (2012). Cities as dissipative structures: Global change and the vulnerability of urban civilization. In M. P. Weinstein, & R. E. Turner (Eds.). *Sustainability science: The emerging paradigm and the urban environment.* London (UK): Springer.

Richardson, A. (2016). *Dismantling the Wall: the simplification of complex socio-technological systems and the implications for urban resilience*.

Rink, Dieter, & Thomas, Arndt (2016). Investigating Perception of Green Structure Configuration for Afforestation in Urban Brownfield Development by Visual Methods-A Case Study in Leipzig, Germany. *Urban Forestry and Urban Greening, 15*, 65–74.

Rockstrom, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., III, Lambin, E. F., ... Foley, J. A. (2009). A Safe Operating Space for Humanity. *Nature, 461*(September), 472–475.

Scuderi, M., & Rahm, P. (2014). *Constructed atmospheres.* [Postmedia books].

Stremke, S., & Van den Dobbelsteen, A. (2013). In Taylor & Francis Group (Ed.). *Sustainable energy landscapes*http://dx.doi.org/10.1201/b13037.

Swyngedouw, E., & Kaika, M. (2014). Urban political ecology. great promises, deadlock… and new beginnings? *Documents d'Analisi Geografica, 60*(3), 459–481. http://dx.doi.org/10.5565/rev/dag.155. [http://org/(/DOI] http://org/.

Tanner, C. J., Adler, F. R., Grimm, N. B., Groffman, P. M., Levin, S. A., Munshi-south, J., ... Wilson, W. G. (2014). Urban ecology: advancing science and society In a nutshell. *Frontiers in Ecology and Evolution, 12*(10), 574–581.

Vallero, D. A., & Braiser, C. (2008). *Sustainable design. The science of sustainability and green engineering.* Wiley.

Vandevyvere, H., & Stremke, S. (2012). Urban planning for a renewable energy future: methodological challenges and opportunities from a design perspective. *Sustainability, 4*(12), 1309–1328. http://dx.doi.org/10.3390/su4061309.

Von Schilling, C., & Straussfogel, D. (2008). Introducing the research. Entropy debt: a link to sustainability? *52nd annual meeting of the international society for the systems sciences*.

Wolch, J. R., Byrne, J., & Newell, J. P. (2014). Urban green space, public health, and environmental justice: The challenge of making cities just green enough. *Landscape and Urban Planning, 125*, 234–244. http://dx.doi.org/10.1016/j.landurbplan.2014.01.017.

Ye, H., He, X. Y., Song, Y., Li, X., Zhang, G., Lin, T., & Xiao, L. (2015). A sustainable urban form: The challenges of compactness from the viewpoint of energy consumption and carbon emission. *Energy and Buildings, 93*, 90–98. http://dx.doi.org/10.1016/j.enbuild.2015.02.011.

Ying, L. (2015). Twin universes: Universal laws of thermodynamics. *American Journl of Modern Physics, 4*, 1–4. http://dx.doi.org/10.11648/j.ajmp.s.2015040101.11.