Reducing Urban Entropy Employing Nature-Based Solutions: The Case of Urban Storm Water Management

Raffaele Pelorosso, Federica Gobattoni and Antonio Leone

Abstract This paper presents the theory behind the concept of low-entropy cities based on the second law of thermodynamics. This concept aims to provide a bridge among different approaches on city sustainability studies, highlighting the links between natural processes and the socio-ecological complexity of urban systems. A practical low-entropy application is then proposed for urban storm water management, examining the planning of nature-based solutions with the support of a modelling approach. A further novelty of this work is the attempt to combine entropy with resilience assessment for urban green infrastructure planning.

1 Introduction

In a previous work (Leone et al. 2016), the authors highlight the importance of taking the laws of thermodynamics into consideration when planning actions to improve the sustainability of cities and landscapes. In particular, a SLT approach, also defined as "second-law thinking", is proposed as a planning paradigm aimed at increasing exergy (i.e. the energy component able to produce work) and, consequently, at reducing the production of wastes (entropy) which impede the functionality of the socio-ecological system. In this work, we explore another aspect of SLT, the entropy concept. Entropy is a measure of the disorder, or waste of the city, and as such can be considered an indicator of the diversified impacts of the urban development on the biosphere.

The entropy release of a city today is excessive because it overcomes Earth's natural capacity of regeneration and threatens to destabilise the urban (human) civilization itself, which is causing it.

Indeed, a link has clearly been established between consumption processes (also in terms of soil sealing, and relative waste productions) and social-environmental

R. Pelorosso (✉) · F. Gobattoni · A. Leone
DAFNE, Tuscia University, Viterbo, Italy
e-mail: pelorosso@unitus.it

R. Papa et al. (eds.), *Smart Planning: Sustainability and Mobility in the Age of Change*, Green Energy and Technology,
https://doi.org/10.1007/978-3-319-77682-8_3

problems (e.g. increasing soil erosion, decreasing biodiversity, climate change and migration), which are all consequences of the natural response by Gaia to the human imposed constrictions on the irreversible growth of global entropy (Costanza et al. 2012; Fistola 2011; Gobattoni et al. 2011; Karnani and Annila 2009; Lovelock and Margulis 1974).

Recently, a new thermodynamic concept of cities has been proposed to support a more systematic evaluation of the urban system sustainability (Pelorosso et al. 2016a). In particular, Pelorosso et al. (2017) propose a low-entropy urban green infrastructure (UGI) planning strategy and several entropy indicators to face the main environmental, social and economic phenomena affecting urban systems. The low-entropy city approach can lead to a reduction in consumption, but more importantly, it aims to investigate what is consumed, how energy and matter are used and where waste might induce socially and environmentally negative consequences.

Nature-based solutions (NBSs) are engineered green/ecological systems inspired or supported by, or copied from, Nature (EU 2015). NBSs are part of UGI, examples include Sustainable Urban Drainage Systems (SUDS) or urban BMPs to control pollution, runoff and, in general, to ensure a sustainable urban water management. These include green roofs, pervious surfaces, constructed wetlands, detention basins, infiltration basins and filter drains (Pelorosso et al. 2013; Recanatesi et al. 2017). Such NBSs aim to regulate the water cycle through their adsorption, stoking and infiltration capacities and then they represent potential sustainable solutions for the reduction of city entropy.

The objective of this contribution is to present a first application of the low-entropy city concept in the context of UGI planning aimed at optimizing the storm water cycle and thus reducing its negative impacts on urban and extra-urban systems. Accordingly, some new indicators are used to evaluate the entropy of an urban system in terms of water quantity and quality parameters in a base scenario and a NBS scenario. The latter is proposed with the aim of increasing the system's hydrological resilience (Pelorosso et al. 2018). The variation in entropy indicator values shows the operational potential of the low-entropy concept for storm water management in urban contexts as well as being the first proposed integration of entropy and resilience concepts in UGI planning.

2 The Low-Entropy City

Every single living organism of the landscape, Man included, uses and exchanges energy and matter (e.g. fossil fuels, solar radiation, organic matter, food, minerals, soil) struggling to develop highly (social-ecological) ordered, lower entropy structures to increase the total dissipation of energy and maximize the global production of entropy (at Earth scale) following the Second Law of Thermodynamics (SLT). Man, more than other species, plays a fundamental role in the evolution process of the global system due to our ability to modify the biosphere (and consequently, the landscape) drastically in order to reach our objectives (Norra 2014; Pasimeni et al. 2014).

Cities can be seen as open systems and, according to the SLT, they can increase their socio-ecological structure and complexity (negentropy) only by increasing the disorder and random-ness (entropy) in their host system, the biosphere.

Thus, low-entropy cities are urban systems with lower entropy release into the biosphere adopting strategies that mimic, as far as possible, Nature and the structure and functioning of ecosystems according to the SLT and the circular economy of Nature (Ho 2013). A low-entropy city will therefore evolve and grow enhancing its socio-ecological and structural complexity (reducing internal entropy) by adding and optimizing functional elements and synapses among them while wastes (exported entropy to the biosphere) are minimized. Entropy exported to the biosphere is represented by direct and indirect city wastes. Direct wastes derive from urban metabolic cycles of socio-ecological and technical systems, indirect wastes are produced by unsustainable extraction of resources in source countries and ecosystems in order to sustain the same urban system.

In this work a first application of this concept is presented in the context of storm water management and NBS planning.

3 Nature-Based Solutions and Second Law of Thermodynamics

Cities are human-modified complex ecosystems (Bai 2016) and associations between natural and urban processes are possible.

In nature, an ecosystem such as a forest, has no useless features because each component has a role in the functioning of the whole system. An open space within a dense forest created by tree falls can host colonizing plant species, can be a habitat for wild fauna that spread seeds or pollinate flowers allowing a complex ecosystem to evolve and regenerate maintaining sufficient levels of identity and essential resources (e.g. soil fertility). The bark on the sunny side of a tree trunk may host a most beautiful orchid, while the shady side supports an incredible lichen community. All these organisms appear and grow in a suitable habitat because they have evolved to use the free available energy present in that site and those conditions. In natural ecosystems, very little energy is wasted but instead it is stored (e.g. as biomass) and transformed into different forms that can be used by other organisms for the benefit of the whole system. Similarity and in a scalar and fractal manner, a cell plays its role in an organism, a cell sub-component within that cell. All the components of an organism (from unicellular to an entire ecosystem) carry out a role in the evolution of the upper system through cooperation and competition mechanisms that often can be observed and understood only from the highest levels of the system (Capra and Luisi 2014).

Good farmers apply rotational crop management, recycle and reuse everything in their productivity systems (Ho 2013; Leone et al. 2014). Entrepreneurs restructure, close or sell inefficient society components. Engineers reduce heat loss and employ used heat to support other industrial processes, thus increasing global efficiency. Like these examples, in a low-entropy city view, urban planners should aim to pursue social-economic objectives employing all available and free forms of energy, defining the best employment or, at least, the main green strategies for different underused and unused urban spaces that represent an opportunity for transformation and urban regeneration (Gobattoni et al. 2016; Pelorosso et al. 2017).

In a SLT view, NBSs providing several UESs (e.g. climate or water regulation) are able not only to use the incoming solar energy and rainfall, stocking it in biomass or in the soil layer, but also to reduce the dispersion of entropy and low-value forms of energy such as reflected radiation, radiant temperature or water runoff and associated pollutants. Clearly, following the low-entropy concept, NBSs should be planned where excessive or unused energy, water and wastes are present. Indeed, NBSs must be adapted to local conditions to be energy and resource-efficient and resilient to change (EU 2015).

4 Study Case

The considered study area has an extension of about 330 ha and corresponds to the second municipality of the Bari Metropolitan Area (Fig. 1) where the urban drainage network is inadequate to manage storm water runoff efficiently. The combined sewer system, during heavy precipitation events, is not capable of managing all the volumes. Consequently the overloads affect the urban system, flowing directly to the seafront, contaminating the adjacent public beaches with obvious consequences on health and fruition.

5 Methods

In this work, some new indicators are used to evaluate the entropy of the urban system in terms of water quantity and quality regulating capacity. A base (status quo) scenario has been modelled and subsequently compared with a Nature-based scenario, proposed to increase the hydrological resilience (Pelorosso et al. 2018). The difference in entropy indicators shows a clear potential for implementation of the low-entropy approach for the storm-water management in urban contexts.

Few applications of the entropy concept have been presented in a context of spatial urban planning (Balocco and Grazzini 2000; Fistola and La Rocca 2014) and, to our knowledge, none within urban storm water management. Pelorosso et al. (2017) propose new kinds of entropy indicators intended to be easily employable by urban planners with the support of a modelling/assessment approach similar to

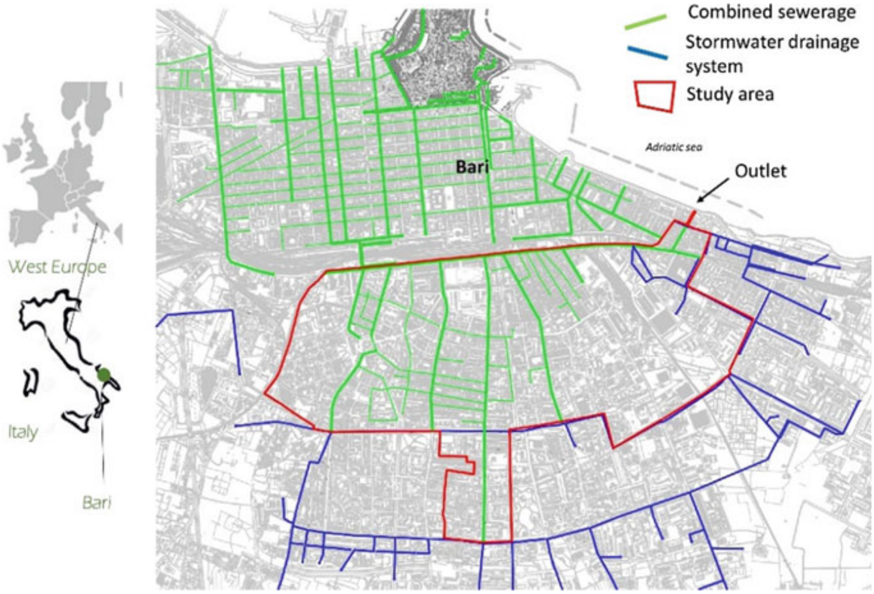

Fig. 1 Study area

Table 1 Entropy indicators and NBSs for urban storm water management (modified from Pelorosso et al. 2017)

Low-entropy nature-based solutions	Diffuse NBSs (green roofs, permeable pavements and bio-retention basins)	End-of-pipe NBSs (phytoremediation plants, wetlands)
Internal entropy indicators		
Ecological complexity	n° and typology of NBS	n° and typology of species, local freshwater ecosystems health status
Social complexity	People and water enterprises	People and water enterprises
Structural/physical complexity	% infiltration or stored water	Re-used water
External entropy indicators		
Biosphere/regional complexity	Outlet flooding, global runoff	Health status of receiving freshwater and sea ecosystems, CO_2 emission

that presented herein. Table 1 reports the entropy indicators proposed by Pelorosso et al. (2017) to evaluate a NBS scenario in terms of urban storm water management efficiency following a SLT view.

The proposed indicators have an explicit spatial character to allow for practical decisions on urban planning. They are classified in two groups: internal and external entropy indicators. Internal urban system complexity (internal entropy) can be increased by NBSs and it is divided into ecological, social and structural/physical complexity. Internal entropy indicators can therefore help to measure UGI socio-ecological cycles within urban systems (see Sect. 2). External entropy indicators measure the impact of urban systems on external areas. The identification of the borders of open systems such as cities is a hard issue. Nevertheless, such external areas can be identified at local scale, with opportune justifications, for a real pragmatic and operative planning (Pelorosso et al. 2017).

In this work, we propose more detailed entropy indicators adapted to the specific study case. Specifically, only structural/physical complexity is presented leaving further assessments to a future research development. External indicators are referred to the outlets of each sub-basin and at the outlet of the whole urban catchment that converges to the treatment plant. It is worth mentioning that water amount can exceed the overflow weir at the outlet of the study area during critical rainfall events. At such times, the entropy (waste) is not managed by the treatment plant and is discharged into the sea by the drainage pipe directly.

All the following entropy indicators are derived from the outputs obtained through the implementation of the US-EPA managerial model called Storm Water Management Model (SWMM, release 5.1.012), which is a well-recognized tool for dealing with storm water management issues (Zhou 2014). The simulated critical rainfall event has a three hour duration (equal to the concentration time of the urban catchment) and a return period of five years (as requested by Italian technical legislation for urban drainage systems) (Pelorosso et al. 2016b).

Two internal entropy indicators, E^i, have been proposed to evaluate the efficiency of the actual land use assemblage in terms of SLT

$$E^i_{infiltration\_j} = \frac{infiltration\,(\text{mm})_j}{rainfall\,(\text{mm})_j}. \tag{1}$$

$E^i_{infiltration\_j}$ describes the amount of water infiltrated into a sub-basin j with respect to the total amount of rainfall in the sub-basin j. It can be used to determine the efficiency of the current land use in terms of groundwater recharge for the sub-basin j. The hypothesized groundwater recharge would allow local use of water and the maintenance of a healthy status for green areas (e.g. urban trees, parks)

$$E^i_{storage\_j} = \frac{storage\,(\text{mm})_j}{rainfall\,(\text{mm})_j}. \tag{2}$$

$E^i_{storage\_j}$ describes the amount of water stocked in a sub-basin j with respect to the total amount of rainfall in the sub-basin j. It is related to the efficiency in water reuse for UES provision (e.g. biodiversity support or irrigation for local food or non-food production).

Both indicators can be used to design more liveable environments with positive potential outcomes in social and cultural terms, such as the possibility of creation of green meeting points, urban gardening etc.

The other proposed external entropy indicator, E^e, considers quantitative and qualitative water parameters:

$$E^{e}_{overflow\_j} = \frac{overflow\,(\mathrm{L})_j}{inflow\,(\mathrm{L})_j}. \tag{3}$$

$E^{e}_{overflow\_j}$ takes into consideration the efficiency of the drainage system in managing water runoff. The measurement is realised in the node of the drainage system related with sub-basin *j*. In this case, it describes, for each node *j*, the amount of combined sewerage overflow during the simulated rainfall event divided by the total inflow into the same node due to sub-basin runoff and the current pipe load

$$E^{e}_{sewagedischarge\_s} = \frac{Total\ volume\,(\mathrm{L})_s}{rainfall\,(\mathrm{L})_s}. \tag{4}$$

$E^{e}_{sewagedischarge\_s}$ describes the efficiency of the green and grey infrastructure in managing the total amount of rainfall at whole system level. Total volume is the amount of discharge (L) at the final outlet; rainfall is the total amount (L) of rainfall in the whole system *s*

$$E^{e}_{TSS\_j} = \frac{TSS\,washoff\,(\mathrm{kg})_j}{area\,\left(\mathrm{m}^2\right)_j}. \tag{5}$$

$E^{e}_{TSS\_j}$ describes the Total Suspended Solid (TSS) produced in a sub-basin *j* by washoff related to the total area of sub-basin *j* producing the TSS. *TSS* is listed as a potential pollutant by the Handbook of Urban Runoff Pollution, Prevention and Control Planning (US EPA 1993) and is widely recognized as a conventional contaminant in the international scientific literature (Borris et al. 2014; Hilliges et al. 2017; Revitt et al. 2014). TSS may have negative impacts on natural Habitat and on aesthetic and recreational value, may cause and/or increase erosion phenomena and transport pollutants (US EPA 1993)

$$E^{e}_{TSS\_overflow\_j} = \frac{TSS\,overflow\,(\mathrm{kg})_j}{TSS\,inflow\,(\mathrm{kg})_j}. \tag{6}$$

$E^{e}_{TSS\_overflow\_j}$ considers the amount of TSS into the overflow of each node. It describes the efficiency of the drainage system in managing the TSS coming from a sub-basin *j* plus the current TSS load in the upstream pipes

$$E^{e}_{TSS\_s} = \frac{TSS\,(\mathrm{kg})_s}{area\,\left(\mathrm{m}^2\right)_s}. \tag{7}$$

$E^{e}_{TSS\_s}$ describes the efficiency of the green and grey infrastructure in managing the total amount of TSS at whole system level *s*.

It is worth noting that indices (1, 2, 3, 4, and 6) are unit-less, while indices (5) and (7) are expressed in (kg/m^2). All these entropy indicators give us a measure of the system's efficiency in terms of quantitative and qualitative water parameters but, most importantly, they provide us with a measure of the spatial distribution of wastes (entropy) with respect to certain fixed variables relating to the context of the study case (specific morphological characteristics of the basin and sub-basin, green and grey infrastructure) and the simulated rainfall event. Following a SLT view, planners and designers should then analyse the proposed entropy indicators in order to increase and optimize the local reuse of water (as described by the internal entropy indicators 1 and 2) and reduce wastes or even transform them into a resource for other metabolic activities (as described by external entropy indicators, 3, 4, 5, 6, 7). Finally, a composite indicator of external entropy at sub-basin scale is calculated as the sum of standardized entropy indicators $E^{e}_{overflow\_j}$, $E^{e}_{TSS\_j}$ and $E^{e}_{TSS\_overflow\_j}$ obtained by dividing each one by the maximum value registered in the base scenario. This index of external entropy was then reclassified in three classes and mapped to add further judgment criteria about the spatial distribution of critical points amongst the different sub-basins.

6 Results

Figure 2 shows the spatial distribution of the entropy indicators calculated at sub-basin scale. In map 2a, b an inverse colour scale has been used since high values of the indicators represent more internal complexity (i.e. water infiltration and storage) and then more possibilities for water reuse and an increase in system complexity. The distribution of these indices shows a reduced functionality of the system for sustainable storm-water management. The external entropy indicators show several critical sub-basins (see also the composite indicators of Fig. 2f), mostly in the south-central part of the study area, with particular reference to the sub-basins 40, 37, 17, 31, 22 and 33. At the final outlet, entropy indicators at system level report: (a) a water volume discharge of around half of the total rainfall volume, (b) a mean TSS of 2.3 kg/ha produced by the whole basin (Table 2).

The variation in entropy in the NBS scenario can be evaluated at system (Table 2) and sub-basin scale (Table 3). Internal entropy indices show a slight increase in values with respect to the base scenario where the infiltration and storage of stormwater processes were proximate to zero due to the high imperviousness of the urban district. A significant reduction in external entropy indices is shown in the sub-basins where the introduction of NBSs and the grey infrastructure re-design are proposed. Moreover, two sub-basins (nos. 39 and 41) display an entropy reduction above all

Table 2 External entropy indicators at system level

Entropy indicator	Base scenario	NBS scenario	Δ%
$E_{sewagedischarge\_s}$ (Eq. 4)	0.518	0.513	−0.965
E_{TSS_s} (Eq. 7)	2.328	2.283	−1.968

Base scenario and NBS scenario

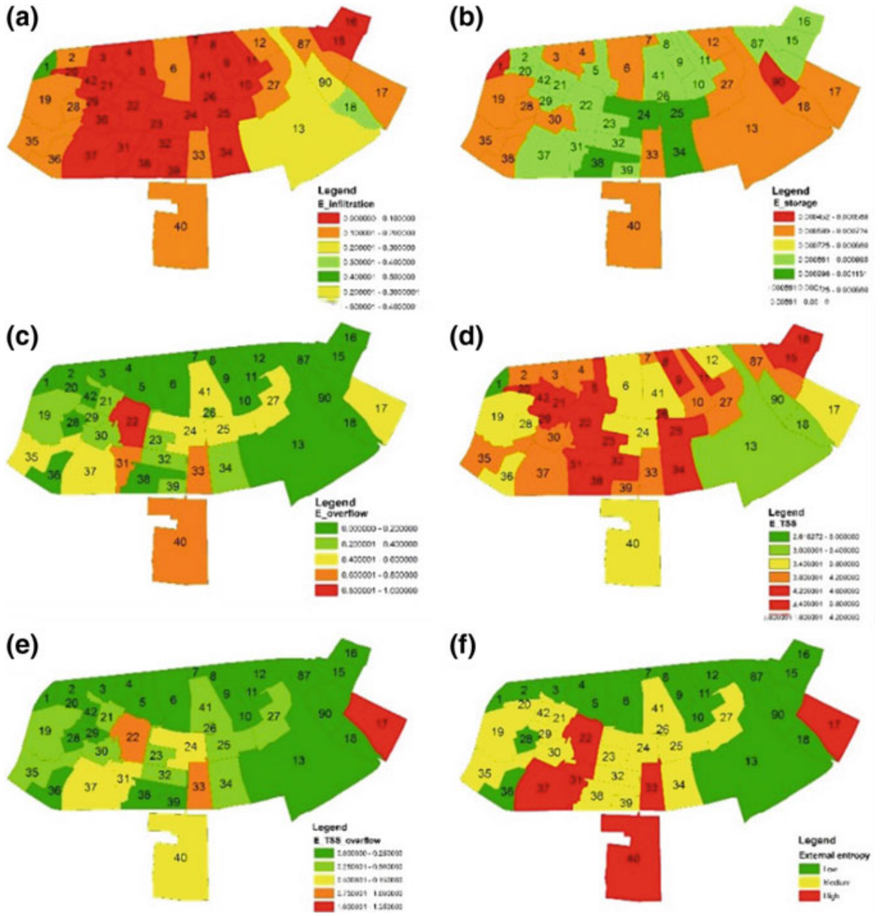

Fig. 2 Indicators of internal entropy **a**, **b**, external entropy **c**–**e** and composite external entropy (**f**) at sub-basin scale

in terms of overflow as they are downstream to the proposed interventions and they receive a smaller amount of sewerage inflow.

7 Discussion and Conclusions

The strength of thermodynamics is its ability to describe whole systems and aggregate properties, on macro scales, that emerge from complex micro-scale processes (Bristow and Kennedy 2015). Despite the widespread scientific awareness of thermodynamics as a key for interpreting evolution mechanisms, practical ways to employ it in land use decision making, landscape ecology and urban planning are challeng-

Table 3 Variation in entropy indicators at sub-basin scale

Sub-basin	Proposed intervention	Δ $E_{infiltration}$	Δ $E_{storage}$	Δ% $E_{overflow}$	Δ% E_{TSS}	Δ% $E_{TSS\_overflow}$
17	Infiltration basin	0.05	0.18	−23.88	−50.94	−60.22
24	Extensive green roof	0.20	0.07	−46.13	−21.73	−51.77
37	Permeable pavement	0.56	0.00	−33.72	−59.07	−34.60
39		0.00	0.00	−100.00	0.00	0.00
40	Grey infrastructure project	0.00	0.00	−18.25	0.00	−18.26
41		0.20	0.07	−12.83	−21.21	−12.68

Only sub-basins with significant variation in entropy are reported. $E_{infiltration}$ and $E_{storage}$ variations are expressed in absolute values

ing. In practice, entropy and the second law of thermodynamics tend to be applied only metaphorically, while the required equations and parameters are often abstract quantities and are not usually available to and manageable by land managers and urban planners (Cushman 2015; Filchakova et al. 2007; Pelorosso et al. 2011; Leone 2014). There is also a need for hierarchical levels and multi-scale processes to be investigated in greater depth than is generally the case. In contrast, real sustainable futures and cities need to be designed under the lens of thermodynamics as they are the fundamental laws of universal evolution (Leone et al. 2016; Rees 2012).

The proposed entropy indicators represent new tools towards sustainable land-use decision making. This work shows how a quantitative modelling assessment approach could be successfully applied in urban planning practice while dealing with green infrastructure and grey infrastructure design. However, in this work, only the entropy release associated to hydrological processes is studied and further research is therefore necessary both to define entropy more appropriately in ecological/environmental terms (e.g. impact on urban climate, biodiversity) and to investigate possible implications on social aspects (Pelorosso et al. 2017).

The integration of the SLT into the planning of NBSs will require a transdisciplinary approach with a proactive contribution from different research fields and experts. Proposed assessment methodology and entropy indicators can be used to evaluate different NBS scenarios and/or to guide the design process in building low-entropy cities with multifunctional UGI components. An example of this multi-perspective view-point implementation is presented in another work (Pelorosso et al. 2018), where an integrated climate resilience and vulnerability assessment allows the best NBSs to be allocated to the most suitable areas. The choice and the spatial localization of NBSs would therefore focus on the optimization of UGI multifunctionality, considering SLT (i.e. available and recyclable water or intercepted waste), resilience (i.e. adaptive and recovery capacity) and a UES viewpoint (e.g. number and typology of beneficiaries). This work, using the scenario NBS coming from (Pelorosso et al. 2018) can thus be considered as a first step towards the integration of the resilience and entropy concepts into a process of sustainable planning of urban systems.

References

Bai X (2016) Eight energy and material flow characteristics of urban ecosystems. Ambio 45(7):819–830

Balocco C, Grazzini G (2000) Thermodynamic parameters for energy sustainability of urban areas. Sol Energy 69(4):351–356

Borris M, Viklander M, Gustafsson AM, Marsalek J (2014) Modelling the effects of changes in rainfall event characteristics on TSS loads in urban runoff. Hydrol Process 28(4):1787–1796

Bristow D, Kennedy C (2015) Why do cities grow? Insights from nonequilibrium thermodynamics at the urban and global scales. J Ind Ecol 19(2):211–221

Capra F, Luisi PL (2014) Vita E Natura: Una Visione Sistemica. Aboca

Costanza R et al (2012) Sustainability or collapse: what can we learn from integrating the history of humans and the rest of nature. Ambio 36(7):522–527

Cushman SA (2015) Thermodynamics in landscape ecology: the importance of integrating measurement and modeling of landscape entropy. Landscape Ecol 30(1):7–10

EU (2015) Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities. Final Report of the Horizon 2020 Expert Group on 'Nature-Based Solutions and Re-Naturing Cities'

Filchakova N, Robinson D, Scartezzini JL (2007) Quo Vadis thermodynamics and the city: a critical review of applications of thermodynamic methods to urban systems. Int J Ecodyn 2(4):222–230

Fistola R (2011) The unsustainable city. Urban entropy and social capital: the needing of a new urban planning. Procedia Eng 21:976–984

Fistola R, La Rocca RA (2014) The sustainable city and the smart city: measuring urban entropy first. In: The sustainable city, vol IX. WIT Press, p 537

Gobattoni F, Pelorosso R, Leone A (2016) Strategie Di Riqualificazione Urbana Clima-Adattiva: Nature-Based Solutions per Città Più Resilienti. Planum 101–110

Gobattoni F, Pelorosso R, Lauro G, Leone A, Monaco R (2011) A Procedure for mathematical analysis of landscape evolution and equilibrium scenarios assessment. Landscape Urban Plan 103(3–4):289–302

Hilliges R, Endres M, Tiffert A, Brenner E, Marks T (2017) Characterization of road runoff with regard to seasonal variations, particle size distribution and the correlation of fine particles and pollutants. Water Sci Technol 75(5):1169–1176

Ho M-W (2013) Circular thermodynamics of organisms and sustainable systems. Systems 1(3):30–49

Karnani M, Annila A (2009) Gaia again. Bio Syst 95(1):82–87

Leone A (2014) Planificación, Fisica de La Complejidad, Entropía. Cerrar La Brecha Entre Los Principios Teoricos Y La Praxis. Plurimondi VII(15):141–167

Leone A, Gobattoni F, Pelorosso R (2014) Sustainability and planning: thinking and acting according to thermodinamics laws. J Land Use Mobility Environ (special issue eighth international conference INPUT)

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: Papa R, Fistola R (eds) Smart energy in the smart city. Urban planning for a sustainable future. Springer International Publishing, Berlin pp 83–101

Lovelock James E, Margulis Lynn (1974) Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis. Tellus A 26(1–2):1–2

Norra Stefan (2014) The biosphere in times of global urbanization. J Geochem Explor 147:52–57

Pasimeni MR et al (2014) Scales, strategies and actions for effective energy planning: a review. Energy Policy 65:165–174

Pelorosso R, Gobattoni F, Lopez N, Leone A (2013) Verde Urbano E Processi Ambientali: Per Una Progettazione Di Paesaggio Multifunzionale. J Land Use Mobility Environ 6(1):95–111

Pelorosso R, Gobattoni F, Leone A (2016a). Nature-based cities: a low-entropy approach to sustainability. In: Ecosummit conference. Montpellier, France

Pelorosso R, Gobattoni F, Lopez N, Leone A (2016b) Verde Urbano E Regolazione Delle Acque Meteoriche: L'approccio Modellistico Come Base per Nuovi Standard Urbanistici. Sentieri urbani 19:71–77

Pelorosso R, Gobattoni F, Leone A (2017) Low-entropy cities: a thermodynamic approach to reconnect urban systems with nature. Landscape and Urban Planning 168:22–30

Pelorosso R, Gobattoni F, Leone A (2018) Increasing hydrological resilience employing nature-based solutions: a modelling approach to support spatial planning. In: Papa R, Fistola R (eds) Smart Planning: sustainability and mobility in the age of change. Springer

Recanatesi F, Petroselli A, Ripa MN, Leone A (2017) Assessment of stormwater runoff management practices and BMPs under soil sealing: a study case in a peri-urban watershed of the Metropolitan Area of Rome (Italy). J Environ Manag 201:6–18

Rees W (2012) Cities as dissipative structures: global change and the vulnerability of urban civilization. In: Weinstein MP, Turner RE (eds) Sustainability science: the emerging paradigm and the urban environment. Springer, London

Revitt DM, Lundy L, Coulon F, Fairley M (2014) The sources, impact and management of car park runoff pollution: a review. J Environ Manage 146:552–567

US EPA (1993) Handbook: urban runoff pollution prevention and control planning. p 175

Zhou Q (2014) A review of sustainable urban drainage systems considering the climate change and urbanization impacts. Water 6(4):976–992