Heat Island Effects in Urban Life Cycle Assessment

Novel insights to include the effects of UHI and UHI-mitigation measures in LCA for an effective policy making

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<Heading 1> Summary

Urbanization often entails a surge in urban temperature compared to the rural surroundings: Urban Heat Island (UHI) effect. Such a temperature increase triggers the formation of pollutants worsening the urban air quality. Jointly, bad air quality and UHI affect ecosystems and human health. To alleviate the impacts on population and environment, it is crucial to design effective UHI-mitigation measures.

Life cycle assessment (LCA) is an assessment tool able to capture the complexity of urban settlements and quantify their impact. Yet, as currently implemented, LCA neglects the interactions between built environment and local climate, omitting the resulting impacts.

This study reviews the existing literature, showing the lack of studies which organically include the interactions between built environment and local climate in LCA. This forms the basis to identify the unsuitability of the current LCA framework to comprehensively capture the impact of urban settlements. To overcome this limitation, this research offers a pathway to expand the LCA methodology indicating the necessity to (1) couple the LCA methodology with climate models or physical relations which quantify the interactions between local climate and built environment; (2) include novel impact categories in LCA to address such interactions; and (3) use existing or *ad-hoc* developed characterization factors to assess the impacts related to the UHI effect. The LCA community can build on the frame of reference

offered by this research to overcome current limitations of LCA and enable its use for a comprehensive assessment of the impacts of UHI and its mitigation measures.

<Heading 1> Background

Currently ~54% (i.e., ~4 billion people) of the worldwide population lives in cities (The World Bank 2014) and by 2030 this percentage will reach roughly 60%, entailing an increase of 1.5 million km^2 of new urban land (United Nations 2006). Urbanization processes alter the natural energy budget which results in an increase in urban temperature compared to the rural surroundings: Urban Heat Island (UHI) effect (Oke 1982; Landsberg 1981).

Nowadays, UHI is a recurrent phenomenon, not only in big cities like New York, Tokyo, and Delhi, which are experiencing an increase in urban temperature ranging from 1.5 to 8 ˚C (Gedzelman et al. 2003), 7.5–12 ˚C (Tran et al. 2006), and 3.8–7.6 ˚C (Mohan et al. 2009), respectively, but also in medium-sized cities (Steeneveld et al. 2011; Montávez et al. 2000).

UHI has been classified into microscale and mesoscale. Microscale UHI is governed by processes taking place in the Urban Canopy Layer (UCL), which depends on urban roughness. Whilst, mesoscale UHI is located in the Urban Boundary Layer (UBL), which is the layer between the UCL and the temperature inversion layer. UBL-UHI and UCL-UHI are interdependent phenomena, but they are caused by different processes (Oke 1976).

The major causes of UCL-UHI are: anthropogenic heat from transport, domestic heating, and industrial activities (Rizwan et al. 2008); abundant impervious surfaces which lower evapo-transpiration in built environment compared to rural areas (Chandler 1976; Takebayashi and Moriyama 2007; Imhoff et al. 2010); substitution of natural materials with artificial ones featured with different thermal and optical properties, such as lower albedo—as for asphalt—which store more heat than natural materials (Taha 1997; Akbari and

Konopacki 2005; Montávez et al. 2000); decrease in the sky view factor due to high-rise buildings and narrow streets, that prevents nighttime heat dissipation (Landsberg 1981).

UBL-UHI is mainly caused by anthropogenic heat releases from chimneys and stacks (Chen et al. 2009); sensible heat flux coming from the UCL-UHI; increase in the absorption of the short-wave radiation due to the increase in air pollutants; and, sensible heat coming from the capping inversion layer (Oke 1995). UBL-UHI, compared to UCL-UHI, is characterized by a lower gradient of temperature but larger extension (Oke 1976) both vertically and horizontally, as it can extend also for tens of kilometers downwind (Oke 1995).

UCL-UHI phenomena are responsible for an increase in building energy demand for cooling (Santamouris et al. 2015)—which can be as high as 23% for a typical building (Santamouris 2014)— the worsening of water quality (Hester and Bauman 2013), and the formation of primary and secondary pollutants and ground level ozone (O_3) (Kuttler 2008). Jointly, higher urban temperature and worsened urban air quality increase health risks for urban population (Heaviside et al. 2017). Besides, the thermal anomaly in UBL alters the local pressure affecting stability and giving rise to a UHI circulation system (Sarrat et al. 2006) which entails a higher pollutants' concentration compared to rural environs (Oke 1976).

Estimates show that by the 2050s the temperature in 153 cities worldwide will increase by 1.4-3.1°C (Rosenzweig et al. 2018). Consequently, UHI, coupled with global warming and increasingly frequent heat waves (Perkins et al. 2012), risks to make cities inhospitable and harmful places, in the next decades. To avoid this, it is imperative to intervene on cities to mitigate UCL-UHI (hereafter UHI) to decrease urban population vulnerability and impacts on ecosystems.

Increase in urban albedo, substitution of traditional bituminous rooftops with cool or green roofs, and increase in urban vegetation, are among the most common UHI-mitigation measures (Kleerekoper et al. 2012) which local governments are putting in place to adjust to UHI. For instance, in Ohio, the City of Cincinnati's Office of Environmental Quality is promoting, by allowing access to low-interest loans, the substitution of black roofs with green ones to improve air quality and stormwater runoff (City of Cincinnati 2018).

However, often, UHI mitigation strategies are evaluated in the light of just their specific aim. For instance, Portland Council emended a regulation that underpins the conversion of bitumen rooftops into rooftop garden offering a floor ratio bonus (Bureau of Planning and Sustainability 2018). Although green roofs can contribute to mitigate UHI (Li et al. 2014), the increase in floor area entails an increase in building materials that, in turn, impacts the environment. Thus, when an urban policy, aimed at adjusting to local climate, is evaluated exclusively considering its aim but neglecting its potential side-effects or focusing just on one phase rather than on the whole life-cycle, the environmental burden might be shifted from one life cycle stage to another (e.g., from the use phase to the construction phase) or from one spatial scale to another (e.g., from the local scale to the global scale).

To design effective urban policies for a healthier urban environment, it is fundamental to quantitatively assess beforehand their potential effect. To avoid shifting impacts from one phase to the other, such assessments should include the whole set of impacts of the materials and energy used for the UHI mitigation strategy in a life-cycle perspective.

<Heading 1> Cities and LCA: current shortcomings

Among the quantitative methodologies which assess the sustainability of a product, Life Cycle Assessment (LCA) is the most appropriate choice for the application at urban or neighborhood scale, as it avoids shifting impacts from one life cycle stage to another (Loiseau et al. 2012).

Currently, LCA applications to the built environment are mainly comparative assessments of individual buildings. Nevertheless, in recent years, the discourse about the application of LCA to neighborhoods or to urban scale (hereafter, urban LCA) is gaining momentum (Belussi and Barozzi 2015). Some studies about the application of urban LCA exist in published literature (e.g., Lotteau et al. 2017). However, some research pointed out that, often, LCA studies applied to the urban environment focus on a peculiar aspect—for instance, buildings (e.g., Trigaux et al. 2017)—overlooking the complex building-climate interactions within the urban environment (Clark and Chester 2017; Moffatt and Kohler 2008), suggesting to implement such a methodology (e.g., Mirabella and Allacker 2017; Chester et al. 2012).

As the impacts related to the interactions between urban environment and local climate might be significant—as they start when buildings and infrastructures are manufactured and end when they are dismantled—their omission can mislead results and, therefore, decisions. In the current practice, that excludes the impacts of UHI, two LCAs of built assets (e.g., neighborhoods), where one contributes more than the other to UHI, risk to be seen as equal. For instance, the same urban settlement characterized by low urban albedo, in the first case, and high urban albedo, in the second case, would be assessed in the same way although the variation in albedo may influence both UHI and global climate.

Altogether, it results that urban LCAs which omit interactions between urban environment and urban climate are partial and, therefore, stakeholders and decision makers, who rely on such studies, inevitably fail to identify, develop, and implement effective climate change adaptation measures.

<Heading 2> Literature review

At present, no published literature exists which investigates by means LCA methodology the mutual interactions between built environment and local climate and the consequent impacts on human health and ecosystems (see: Supplementary Material). Because this lack is already a shortcoming in the application of LCA to the built environment, we investigated whether such interactions were included in LCA studies about UHI mitigation measures, as they are the main reason why these measures are put in place.

We reviewed the international literature related to the environmental assessment of UHI-mitigation measures, using the keywords “life cycle assessment” and “urban heat island mitigation”. For each article retrieved, we investigated the functional unit in the study; whether the use phase—the phase during which the UHI-mitigation strategies exert their effect on urban climate—was included in the studies; which was the scale of application of the study, in case the results related to the functional unit were extended to a different scale; whether the UHI mitigation effect was included in the LCA results.

Table 1 Literature review of the LCA studies focused on UHI-mitigation strategies

Reference	Mitigation strategy(ies)	Functional unit	Use phase	Scale of application	Inclusion of the effect on UHI in the LCA results	Notes
(Susca et al. 2011)	Cool and green roof	1 m^2	Yes	Building	No	Comparative LCA
(Spatari et al. 2011)	Permeable pavement and street trees	2.66 hectares comprising one block of Stratford Avenue in New York City	Yes	Functional unit	No	The study explores the stormwater runoff reduction related to the substitution of impervious pavements with permeable ones and tree planting
(Bianchini and Hewage 2012)	Green roofs	1 kg of each material composing the green roof	Yes	Urban	No	
(Ottelé et al. 2011)	Green façades and living walls	1 m^2	Yes	Functional unit	No	
(Blackhurst et al. 2010)	Green roof	Replacing about 6.5 million sq ft of traditional roofing with a green roof in an urban neighborhood	Yes	Functional unit	Yes	The impact of the green roof on the UHI has been evaluated just in terms of GHG reduction due to the decrease in energy use entailed by the UHI mitigation
(Kosareo and Ries 2007)	Green roofs	1115 m^2	Yes	Functional unit	No	
(Susca 2012a)	Cool roof	1 m^2	Yes	Functional unit	No	
(Santero and Horvath 2009)*	Pavements	1 km lane (equal to 3600 m^2)	Yes	Functional unit	Yes	The impact from the variation in surface albedo on urban heat island has been calculated through a relationship between albedo and electricity consumption. Then the effect of variation in albedo on energy consumption has been translated into kilograms of carbon dioxide equivalents
(Perini et al. 2011)	Green façade (direct and indirect greening system) and living wall	Not specified in the article	Yes		No	

(Wang et al. 2013)	Bioretention basin, green roof and permeable pavement	Each green infrastructure has the capacity to store the runoff associated with 2.5 cm of rainfall generated over 79 m^3 watershed**	Yes	Functional unit	No	A consequential LCA has been performed in the study
(Feng and Hewage 2014)	Living walls	1 m^2	Yes	Functional unit	No	
(Gargari et al. 2016)	Green roofs	1 m^2	No	Functional unit	No	
(Hong et al. 2012)	Green roofs	An educational building	Yes	Functional unit	No	The study focuses on carbon dioxide life cycle assessment of green roofs
(Smetana and Crittenden 2014)	Urban vegetation (6 lawns)	1 ha lawn in a redevelopment area/urban park	No	Functional unit	No	
(Cubi et al. 2016)	Green and cool roof	1340 m^2 roof of an office building	Yes	Functional unit	No	
(El Bachawati et al. 2016)	White and green roofs	"The construction and installation of a roofing system to cover a surface of 834 m^2 for 45 years"	No	Functional unit	No	
(Strohbach et al. 2012)	Urban parks	"Mass of CO_2"	Yes	Functional unit	No	The Life Cycle Impact Assessment (LCIA)is focused on carbon dioxide
(Saiz et al. 2006)	Green and white roof	A whole building	Yes	Functional unit	No	

* The article is not specifically focused on pavements as UHI-mitigation measures. However, in the calculation of the impacts related to pavements, the authors include the effect of albedo on UHI

** The functional unit for the bio-retention basin, the green roof, and the permeable pavement correspond to 137 m^2, 1298 m^2, and 4047 m^2, respectively

Table 1 shows that about 30% of the studies reviewed is referred to a functional unit of 1 m^2. In this case, the omission of the potential UHI mitigation effect can be justified because the chosen functional unit can hardy exert a measurable UHI mitigation effect. However, the potential application of the results of those studies to larger scales (e.g., urban scale) might imply the exclusion of the accounting of the effect on UHI mitigation. About 60% of the reviewed studies focuses on a functional unit ranging from the rooftop's surface to a couple of hectares. Among those articles, only two investigate the effect of the UHI mitigation strategy on energy demand, but, significantly, none includes the effect on urban temperature, and the consequent impact on air quality and human health.

Although not responding to the keywords used as selection criteria in the literature review, some attempts to include the effect of pavements on UHI in LCA can be found among published studies. Sen and Roesler (2018), Baral et al. (2018), and Sen and Roesler (2017) addressed the potential effect of pavements on UHI, translating them into global warming potential, but they overlooked the impacts on human health and ecosystems. Whilst, Susca (2012b) evaluated the effect of UHI mitigation through the increase in urban albedo and included the potential effect on human health related to urban temperature reduction. However, the effect on the formation of pollutants and on ecosystems remained unexplored.

As LCA studies which comprehensively include the effect of the interaction between built environment and UHI cannot be found in literature, the aim of this study is to conceptualize mechanisms and to offer a pathway to include in urban LCA studies the impacts on human health and ecosystems related to the: (1) interactions between built environment and urban climate (i.e., UHI); (2) effect of the deployment of the UHI mitigation measures.

<Heading 1> UHI and LCA methodology

UHI is a complex and non-linear phenomenon (Voiland 2010). Therefore, to forecast UHI due to new urbanization or to assess the effects of UHI-mitigation strategies, it is necessary to accurately model the urban environment coupling dimensional data, like building and street dimensions, to both physical and optical characteristics of urban materials, and climate data (Mirzaei 2015). Due to the nature of the LCA methodology, the question about how to include an increase in temperature in LCA, as structured by ISO 14040 (International Organization for Standardization 2006a) and 14044 (International Organization for Standardization 2006b), remains open. According to ISO 14040 (International Organization for Standardization 2006a) and 14044 (International Organization for Standardization 2006b), LCA is carried out in four distinct phases: goal and scope definition; inventory analysis; impact assessment; interpretation.

In the following, the most significant aspects of each LCA phase are discussed in light of the novel inclusion of UHI in LCA methodology.

<Heading 2> Scope and functional unit

UHI arises within the built environment, therefore, it should be included in the LCA of an urban settlement to capture and quantify impacts correctly. Urban settlements are quite unique though (Goldstein et al. 2013). No two identical urban settlements exist and the interactions between buildings and local climate are highly dependent on the peculiar climate conditions. Thus, it might result difficult to compare different urban settlements including the effect of UHI on LCA. However, when the functional unit is a specific activity within the urban settlement (e.g., transport) a comparative LCA, including UHI, can be carried out. More importantly, the inclusion of UHI in LCA is vital when comparing different UHI-mitigation strategies applied to the same urban settlement and different options for urbanization.

<Heading 2> **Life Cycle Inventory (LCI)**

"LCI is the phase of the LCA involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (International Organization for Standardization 2006a). In this case, a question about the ontology of UHI in the LCA framework arises. Being UHI mainly thermal energy, deriving from the interaction between built environment and climate, should UHI be considered as an elementary flow and, therefore, included in LCI (Figure 1 A)? Or, should it be considered downward the LCI, as it is a consequence of the interactions between elementary flows (Figure 1 B) of the built environment? We believe that the answer mainly sits with the definition of the functional unit.

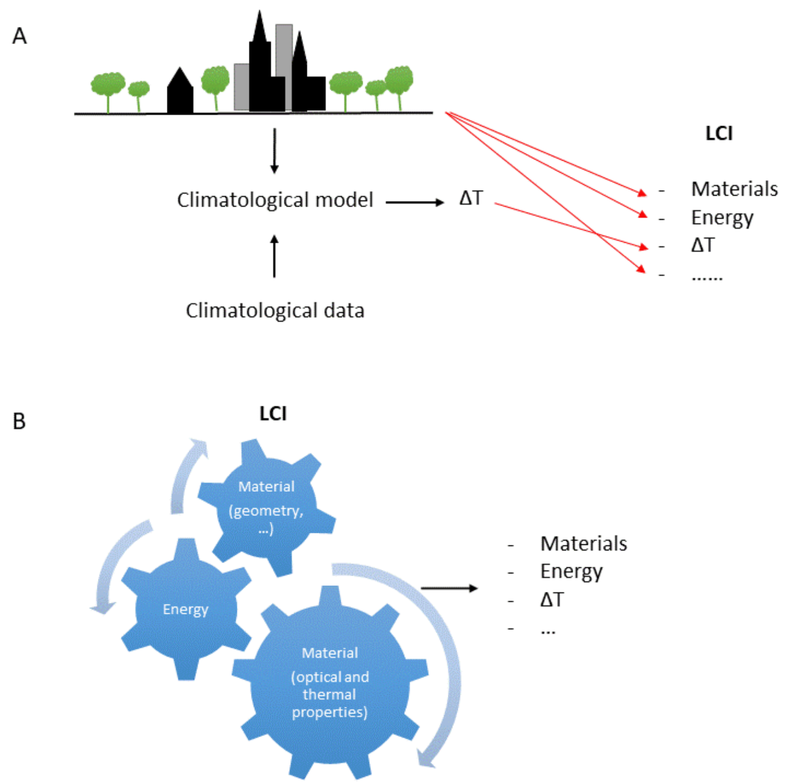

Figure 1 Implementation of UHI-mitigation strategies in LCA. Approaches A) and B)

We developed two distinct approaches to include UHI in LCA methodology.

Approach A relies on a physics-based model, characterized by a spatial resolution, that simulates the interactions between built environment and local climate and provides the consequent variation in urban temperature, which can be entered in LCI. Mirzaei (2015) distinguishes UHI modelling tools into: microscale and city-scale models. In turn, micro-scale models can be divided into: (1) microclimate models, in which the air flows around buildings are computed using computational fluid dynamics (CFD) technique; (2) urban canopy models, in which the airflow model is distinguished from the budget equation. City-scale models integrate both CFD technique and models which include the interactions between solar radiation, cloud cover and soil, but can also use satellite thermal images to correlate land use and land cover to surface UHI (Mirzaei 2015).

Microscale models are preferred for the assessment of the local effects of building orientation, vegetation, dimensional aspects of urban canyons. Whilst, mesoscale models are mainly used to analyze the efficiency of urban policy such as UHI mitigation measures (Mirzaei 2015).

An example of a widely used microscale model for the simulation of buildings-plants-air interactions is ENVI-met (ENVI_MET 2019). ENVI-met is a three-dimensional non-hydrostatic model with a horizontal resolution of 0.5–5 meters which includes the dispersion of air pollutants, such as nitrogen monoxide, nitrogen dioxide and O_3 chemistry. Whilst, the Weather Research and Forecasting (WRF) model is a broadly employed mesoscale numerical weather prediction system model (UCAR), which has been coupled with urban canopy models (i.e., WRF-Urban), in recent years, to: (1) capture the urban land-surface processes to assess the UHI; (2) capture the interactions among UHI, the layer of air beneath the mean height of buildings and trees, and the regional atmospheric conditions (Salamanca et al. 2011); (3) predict the impacts of urbanization on regional weather and climate, public health, and water resources (UCAR 2018).

At present, LCIA is not conducted at spatial scales that allow for characterization of urban-specific environmental burdens. Modeling of micro-scale phenomena such as urban heat islands is critical to producing results that are locally relevant for municipal decision-making. In the remainder of this study we will focus on microscale.

Approach B is a statistical and spatially aggregated approach that benefits of the mathematical modeling of the predominant physical relationships between the variation in urban parameters and UHI. In published literature, studies which relate materials and/or energy within the built environment to a variation in urban temperature can be found. For instance, Yuan and Bauer (2007) found out that the percentage of impervious surface and surface UHI are strongly linearly correlated (i.e., r^2>0.97). Therefore, the amount of impervious surface can be used as a metric to predict surface UHI. Steeneveld et al. (2011) demonstrated that, urban vegetation and UHI are inversely linearly correlated (i.e., r^2=0.495) for cities in the Netherlands. Such a correlation shows that urban vegetation is a reliable urban parameter to evaluate UHI, and that the increase in urban vegetation is the most effective UHI mitigation strategy for cities in the Netherlands.

As the increase in urban population is one of the main drivers of current and future urban sprawl (United Nations 2006), and consequently of UHI in big and medium-sized cities (Cardoso et al. 2017), we propose, as an example, the use of a mathematical formulation which relates UHI magnitude to the number of urban inhabitants:

$$\Delta T_{U-R\,(Max)} = 2.96 \log P - 6.41 \qquad (1)$$

$$\Delta T_{U-R\,(Max)} = 2.01 \log P - 4.06 \qquad (2)$$

Equations 1 and 2 were developed by Oke (1973), which, through regression analyses, demonstrated the correlation (r^2=0.82) between the dimension of a city, measured by means of its population, and the magnitude of the UHI it produces. In particular, equation

1 relates urban population in Northern America with maximum UHI, whilst, equation 2 refers to maximum UHI formation in relation to the number of urban population in European settlements. Equations 1 and 2 can be used to roughly assess expansion plans as population is a proxy for urbanization and the related land use and land cover change. The use of population to foresee UHI for LCA studies can be beneficial, providing it is compliant with the functional unit declared in the LCA study.

Both when Approach A and Approach B are adopted, the use of specific inputs or of different mathematical formulations to account for the different buildings-climate physical relations, depends solely on the functional unit and on the aim of the LCA study. Therefore, no general comments and no general recommendations, about the approach and the model to use, can be made *a priori*, but the approach to be used has to be chosen depending on the aim and scope of the LCA study to conduct.

<Heading 2> Life Cycle Impact Assessment

UHI impacts may be tiered as direct and indirect. The increase in urban temperature directly affects human health decreasing cold-related impacts in winter, increasing heat-related ones in summer, and affecting ecosystems quality. Concomitantly, UHI can trigger chemical mechanisms, such as the formation of secondary pollutants, which, in turn, affect human health and ecosystems (i.e., indirect impacts).

In LCA methodology, impacts and damages converge into midpoint and endpoint categories, respectively. Some LCA methods look at endpoint and some to earlier impacts along the cause-effect chain. Midpoint categories are defined through midpoint indicators/factors which describe environmental mechanisms. Characterization factors are values used to convert a LCI result into a common unit (International Organization for Standardization 2006a) and to reflect the importance of an LCI input (Bare et al. 2000). Endpoint characterization factors are calculated to reflect the effect of a stressor at the end of the cause-effect chain. Therefore, the environmental impacts are translated into issues of concern like natural resources, human health, and natural environment.

Irrespectively of the approach used (i.e., Approach A or Approach B), the variation in urban temperature converges (i.e., classification phase) in a Life Cycle Impact Category (LCIC) (Figure 2). As the variation in urban temperature is a novel parameter not included in the typical LCA structure, a specific midpoint category—where it can be accounted for—should be created. To differentiate such a category from the category Global Warming Potential (GWP)/climate change, because of its local dimension, we called it: Local Warming Potential (LWP) (Figure 2).

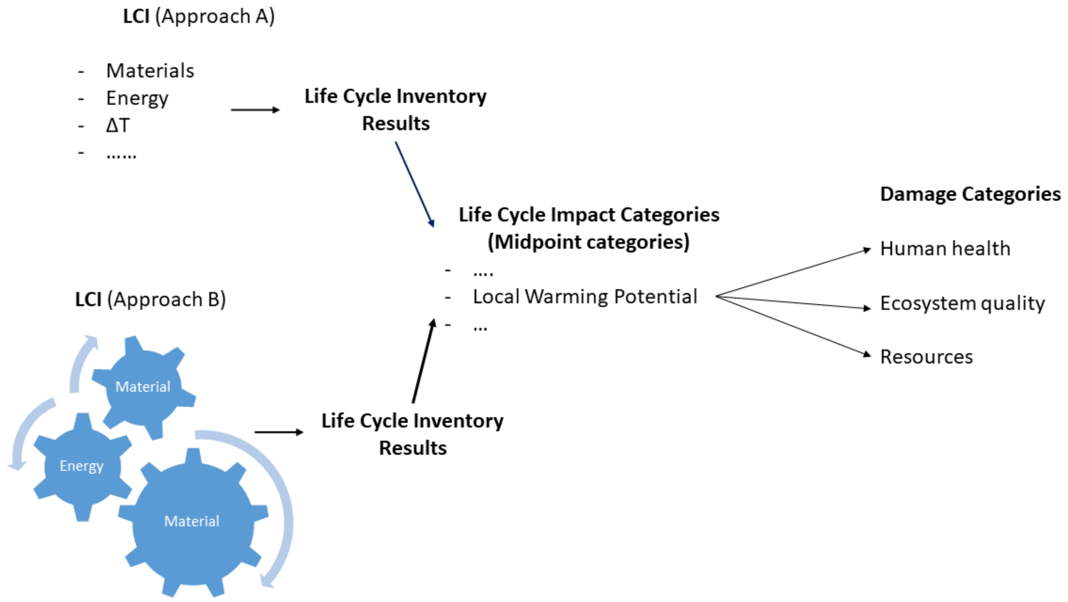

Figure 2 Urban LCA general framework combined with the proposed approaches to address UHI.

A metric for this novel impact category might be “degree Celsius above thresholds”. Thresholds may vary depending on the specific city or the climate area and on the granularity of the conducted assessments.

To foster an urban LCA methodology, a set of *ad-hoc* characterization factors should be developed or retrieved from published literature to include the UHI effects on both human health and ecosystem quality, and to cluster them in the damage categories: resource use; human health consequences; ecological consequences (International Organization for Standardization 2000).

<Heading 3> UHI effects on smog formation

Nitrogen dioxide and volatile organic compounds (i.e., primary pollutants) in presence of stagnant high-pressure, strong solar radiation and high air temperature—typical features of UHI—trigger complex chemical reactions which give rise to O_3 formation (Stone 2005) (i.e., a secondary pollutant) and limit its dissipation (Ooka et al. 2011; Li et al. 2016). Although O_3 formation follows complex and non-linear dynamics—to which contribute numerous factors like the concentration of its precursors, humidity, and solar intensity (Comrie 2012)—high temperature is a key driver because it accelerates its generation (Tao et al. 2003, 2013). Walcek and Yuan (1995) found out that, under polluted conditions, O_3 formation increases by 0.5-1 [$ppb \cdot h^{-1}$] for each 10 ˚C rise. This finding can be easily and widely used whenever an evaluation of O_3 formation is required.

A site-specific study by Stathopoulou et al. (2008) showed that, in greater Athens area, a good linear correlation between the variation in air ambient temperature and the variation in tropospheric O_3 concentration exists. The results of such a study can be applied to future urban LCA studies related to Athens providing a reliable evaluation of the effect of UHI on O_3. Yet, the results cannot be expanded to other cities as they are city-specific for Athens.

Moreover, as the urban environment is often featured with a higher concentration of pollutants compared to the rural environs (Crutzen 2004), some studies investigated the interaction between UHI and urban pollution showing that: PM is the major pollutant and local sources, like traffic, are the major emitters (Bonn et al. 2016; Lutz 2013). In turn, urban pollution influences the amount of incoming solar radiation (Li et al. 2018), and, as a consequence, UHI. Furthermore, as the turbulent mixing entailed by UHI increases the height of the urban boundary layer (Fallmann et al. 2016), the concentration of PM10 decreases showing that UHI and urban pollution intensity are inversely correlated in summer (Li et al. 2018).

<Heading 3> UHI effects on water quality

The wide use of impervious surfaces, such as asphalt pavements and bituminous rooftop, combined with urban temperature increase can affect storm-water runoff (IPCC 2007). The heated rain-water that enters water bodies, like rivers and ponds, affects the metabolism and the reproduction of aquatic species (US EPA 2014).

At present, the effect of thermal pollution in aquatic environments is still scarcely investigated. However, Verones et al. (2010) developed a fate and effect model to calculate the characterization factors to quantify the potential disappearance of aquatic species due to freshwater thermal pollution. In detail, Verones et al. (2010) evaluated the potentially disappeared fraction (PDF) of aquatic species for direct temperature-induced mortality due to a change in ambient river temperature. The use of such a characterization model would be useful whenever urban LCA studies include the assessment of the impacts of urban wastewater on river.

<Heading 3> UHI effects on resources

UHI can significantly affect building energy demand, increasing cooling load in hot and warm climates and decreasing heating load in cold ones (Santamouris 2014). US EPA (2008) found that in the 20-25 °C range, to every 0.6 °C increase in summer air temperature corresponds an increase of 1.5-2% in the peak of electricity demand for cooling. In case Approach B is used to include the effects of the interactions between an urban settlement and local climate, the excess in energy use due to UHI is included downstream LCI and then its impacts calculated. Whilst, when Approach A is preferred, the excess in building energy use is directly included in LCI. In turn, the variation in building energy use impacts the downstream impact categories and, in a cascade effect, all the related damage categories.

<Heading 3> UHI effects on human health

The effect of UHI on human health is a crucial issue. Under non-extreme heat conditions, ~40% of the total heat deaths in London are attributable to UHI, with 47% of UHI related deaths happening in massively urbanized areas like “Central London” and 38% in less urbanized areas like “outer London” (Milojevic et al. 2011).

The effect of UHI on human health is highly site-dependent as it varies according to temperature thresholds. Thresholds indicate the limit above which a significant effect on human health can be recorded. Such thresholds may vary according to climate areas. Baccini et al. (2008) show that the apparent temperature thresholds, above which a substantial increase in mortality for cardiovascular and respiratory diseases can be recorded, varies across Europe: 23.3 °C for North-continental cities and 29.4 °C for Mediterranean cities. In urban LCA studies which focus on UHI and/or UHI mitigation, the marginal increase or decrease in urban temperature can be used to calculate the effect on human health above or below such site-specific or climate-specific thresholds.

Following such a logic, Susca (2012b) assessed—through the use of site-specific temperature thresholds and risk ratios—the effect of the mitigation of New York City UHI on human health calculating the avoided daily mortality due to natural causes and translating it into Disability Adjusted Life Years (DALY). Equations 3 – 6 can be used to calculate the number of DALY related to UHI formation due to expansion plans or new urbanization, or related to the application of UHI mitigation measures.

$$N_{Deaths\,UHI} = RR_{UHI}\ N \qquad (3)$$

$$N_{Deaths} = RR\ N \qquad (4)$$

$$\Delta N_{Deaths\,summer} = N_{Deaths\,UHI} - N_{Deaths} \qquad (5)$$

$$DALY = \Delta N_{Deaths\,summer} \sum_i Perc_i\ Exp_i \qquad (6)$$

N_{Deaths} is the number of deaths due to temperatures not affected by UHI (i.e., rural environs); $N_{Deaths\,UHI}$ is the UHI excess in deaths. When equations 3-6 are used to evaluate the impacts of the application of UHI mitigation strategies, N_{Deaths} is the number of deaths in correspondence of the mitigated urban temperature. RR_{UHI} and RR are site-specific or climate specific risk ratios for above threshold temperatures. In detail, RR_{UHI} is the risk ratio for cities affected by UHI and RR is the risk ratio for rural temperatures or for cities without measurable UHIs. RR can also be referred to an urban temperature decrease related to the application of UHI mitigation measures; N is the number of daily deaths for natural causes in summer. $Perc_i$ is the percentage of death for the different ranges of age and Exp_i is the corresponding life expectancy.

Apart from the direct damages due to the variation in urban temperature, also the variation in urban pollutants—such as PM and tropospheric O_3—can affect human health and therefore, it can be accounted for and added to the assessment.

The long-term exposure to O_3 can give rise to both transient and irreversible effects on human health, ranging from the reduction to the deterioration in lung function and early mortality (McKee 1993). In a study carried out on a large cohort in the U.S., Jerrett et al. (2009) observed a 2.9% increase in risk of death from respiratory causes for every 10-ppb increase in exposure to O_3. Besides, Franklin et al. (2007) found that, in the U.S., to an increase of 10µg/m^3 of $PM_{2.5}$ corresponds an increase of about 1% in mortality because of cardiovascular, respiratory and cerebrovascular diseases (Anderson et al. 2012). Steeneveld et al. (2018) combined high urban temperature and air pollution concentration in a health impact unit that accounts for the impact of UHI on human health. This metric might also be used to provide an assessment of the impact of UHI on human health impact category.

Van Zelm et al. (2008) updated the existing characterization models for both O_3 and PM to assess the damage on human health due to the marginal increase in European population intake rate of such pollutants, and translated them into DALY. The updated characterization models can be applied to LWP LCIC to address the impacts on human health and ecosystem quality whenever it is needed by the aim of the study.

<Heading 1> Discussion

Figure 3 highlights two distinct shortcomings that currently affect urban LCA. Firstly, LCA results are incomplete due to the lack of important elements in LCI which would require a completely new impact category to capture the variation in urban temperature. Secondly, the same missing elements from the LCI do not account for—within existing impact categories—the interactions between the built environment and the local climate, like the variation in building energy use or the formation of primary pollutants due to UHI, making LCA results inaccurate.

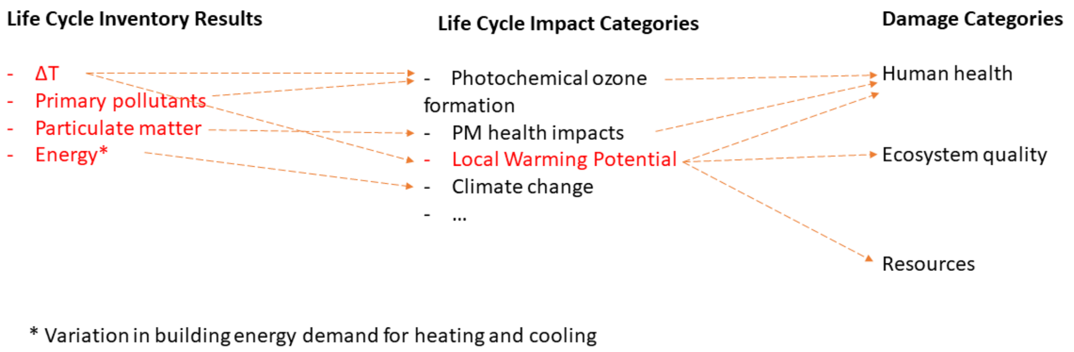

Figure 3 Urban LCA conceptualization. Novel elementary flows and LCIC to be included in LCA (in red). The dotted lines show the potential interactions between the elementary flows, LCICs, and damage categories.

The current study proposes a conceptualization to enhance urban LCA which allows including impacts omitted in previous assessments. At this stage of the research, we suggest to focus on urban/micro-scale as it is the spatial scale where most of the human activities take place. Then, we focus on LCI as the crucial phase to overcome this limitation including the elementary flows that have been so far neglected in urban LCAs.

To assess building-local climate interactions in terms of variation in urban temperature, two approaches have been proposed which differ from LCA mainstream applications: Approach A and Approach B. Trough Approach A, the evaluation of the UHI intensity requires the use of specific site-dependent climate data. The UHI modeling phase requires a peculiar expertise in the field of urban climatology and the use of specific climate models. Conversely, the use of simplified physical relations —Approach B—which reflect the interaction between built environment and local climate, greatly eases the job of LCA practitioners, because it does not require any modeling skill. Nevertheless, such a simplification bears a twofold effect: it can affect the accuracy and, thus, the reliability of the results; and, it can reduce the range of adaptation strategies that can be tested, as simplified empirical physical relations often look at a single urban parameter. Therefore, UHI-mitigation strategies which simultaneously look at multiple parameters could not be assessed. This limitation can be gradually overcome though by future developments in climate and urban science.

As an example, we proposed two tools to quantify UHI magnitude (i.e., ENVI-met and equations 1 and 2), which represent two extremes of a variety of tools and mathematical formulations which can be potentially used, depending on the aim of the urban LCA study.

Equations (1) and (2) express a general physical relationship that can be easily applied to a wide range of studies when population is included in the functional unit of the study or whenever a variation in urban population is known or forecasted (e.g., for urban expansion plans). Although the use of such mathematical formulations greatly simplifies UHI assessment, it also provides coarse results. In particular, equations (1) and (2) provide the maximum UHI value and do not lead to any spatial and temporal differentiation. Therefore, any LCA assessment based on such a value would deliver precautionary values which likely overestimate the effect of urbanization. Furthermore, equations (1) and (2) cannot be used to evaluate the effect of UHI mitigation measures, unless a decrease in urban population is planned.

Contrariwise, the use of ENVI-met requires detailed and site-specific data as inputs: local climate data, dimensional, thermal and optical data related to the urban settlement. The modelling and computation phases for ENVI-met, depending on the urban settlement, are more time-consuming compared to simplified mathematical formulations. However, the outputs of ENVI-met are more informative as they include, for instance, temperature data, relative humidity and pollutant concentration. Furthermore, ENVI-met, as other micro-scale climate models, allows also to concomitantly evaluate the effect of the application of different mitigation measures.

Independently of the approach used, we recommended LWP as an innovative LCIC where the variation in urban temperature can converge (Figure 3). However, such a metric might be reconsidered and refined whenever studies about urban LCA will be further developed or accordingly to the specific scopes and aims of future urban LCA studies.

The creation of a new LCIC requires the development of characterization models, whose accuracy and reliability will depend on the specific advancement in the fields of epidemiology or natural science.

As climate-related impacts on human health and energy use are issues of concern globally, we detected the main effects of variation in urban temperature on human health (both direct and indirect effects), building energy use and water quality. Purposely, we presented characterization models which can be potentially applied to urban LCA studies and that display different granularities, as the choice of a more or a less precise characterization model mainly depends on the goal and scope of the LCA study. Furthermore, the choice of characterization models can depend on the advancements in the field of natural science and on the availability of data about the peculiar local characteristics. For instance, as shown before, the characterization factors for human health and ecosystem quality should be detailed at the regional scale because the impacts in different geographical areas might considerably change.

It has to be highlighted that in future applications of urban LCA methodology to case studies, characterization models have to be accurately chosen to assure a comparable degree of uncertainty to avoid privileging one issue of concern over the others.

Apart from the characterization factors provided here or available in literature, whenever the variation in urban parameters needs to be included in urban LCAs because of the chosen functional unit, *ad-hoc* characterization models might be developed.

Although the present study proposes a crucial progress in LCA methodology, inevitably some limitations occur. Urban settlements are complex, unique and highly site-dependent entities, which make them non-replicable functional units. Therefore, different urban settlements cannot be compared (Albertí et al. 2017). Nevertheless, the conceptualization here described allows the life-cycle comparison between urban policies which foster different urban climate mitigation strategies. This represents an added value to the methodology because no quantitative methodologies, at present, allow for this.

<Heading 1> Conclusions

This study critically reviewed published literature about urban LCA studies, finding that published LCA research systematically omitted interactions between built environment and local climate, and, in particular, the UHI effect. Furthermore, we showed that the assessment's results are both inaccurate and incomplete when LCA is applied to urban settlements, or it is used to evaluate UHI-mitigation measures. Thus, as currently implemented, urban LCA produces results which can potentially mislead stakeholders and decision makers.

To overcome the aforementioned limitations, this study: (1) identifies the potential improvements to include the interactions between the built environment and urban climate; (2) offers potential pathways to integrate UHI and its effects in LCA methodology; (3) suggests the potential indicators and characterization models that might be integrated into LCA methodology. Altogether, the study proposes a significant methodological advancement in LCA to scale it up from building to urban level. A further step would be to assess and develop an appropriate methodology to include the urbanization effects also on regional and global climate.

In addition, the conceptualization proposed paves the way for future research aiming at holistically assessing the environmental performances of cities. This latter is of paramount importance because cities are among major hot-spots of environmental impacts, host or will host the most global population, and ultimately are where the battle for sustainability will be either won or lost.

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