Abstract

Urban areas confront a number of environmental issues including excessive thermal stress and concentrated emissions of greenhouse gases and pollutants. In past decades, many mitigation strategies have been designed and implemented to counteract these issues and ameliorating the environmental quality in cities, which can be broadly classified as white, green or blue infrastructure. The functioning and efficacy of urban mitigation strategies involve complex interactions between landscape dynamics, anthropogenic activities, and atmospheric transport, which leads to compound, rather than singular, environmental impact. In this study, we conducted a critical review of the compound environmental impact of urban mitigation strategies, and evaluated, besides the targeted cooling effect, the resultant co-benefits, trade-offs, or unintended consequence, in terms of building energy saving, air quality improvement, carbon emission offset, and impact to human health. Furthermore, we proposed a novel mathematical framework that is capable of assessing the compound environmental impact in a unified way, together with some preliminary results as the proof-of-concept. A number of knowledge gaps are identified which calls for future transdisciplinary synergy among urban engineers, atmosphere and climate scientists, and epidemiologists.

Keywords: *Air quality; Building energy; Green-blue infrastructure; Heat mitigation; Mathematical framework; Reflective surfaces*

1. Introduction

Global urbanization, the most irreversible and human-dominated form of landuse changes (Seto et al., 2011), has given rise to critical issues challenging the sustainable development of new generation of cities. Here *sustainability* can be broadly viewed as future development that is compatible or supportive to natural environmental systems, human well-being, biodiversity, and ecosystem services and meanwhile maintaining socioeconomic stability and growth. Today, cities and towns accommodate 55% of the global population; this figure is projected to increase to 67% by the mid-century (UN, 2019). The concentration of population in urban areas has positively affected the economic growth, spurring entrepreneurship, inventions, and business innovation (Bettencourt et al., 2007; Bettencourt & West, 2010). In addition, large cities are often "greener" than rural areas, because people living in denser habitats typically have smaller energy footprints, require less infrastructure, and consume fewer resources per capita (Bettencourt & West, 2011).

Despite these benefits, urban areas confront a number of environmental issues, including excessive thermal stress, degraded air quality, concentrated greenhouse gas (GHG) (carbon dioxide CO_2 in particular), and pollutant emissions, infrastructure vulnerability, etc. Among these environmental issues, a prominent example is the phenomenon that urban cores are usually warmer than their rural surroundings, commonly known as the urban heat island (UHI) effect (Oke, 1973; Landsberg, 1981; Oke et al., 2017). The UHI effect can be further aggravated by anthropogenic stressors (Fernando et al., 2010; Sailor, 2011), synergistic interactions with synoptic-scale heat extremes (Perkins, 2015; Jiang et al., 2019), and regional climate changes (Arnfield, 2003; IPCC, 2014).

To counteract the excessive thermal stress in urban areas, urban planners, researchers, and policy makers have designed and implemented numerous heat mitigation strategies. These strategies can be broadly classified into three categories according to their appearance in color, viz. (i) white (reflective), (ii) green (vegetation), and (iii) blue (waterscape) infrastructure. Figure 1 illustrates examples of all three categories of urban mitigation strategies.

Figure 1. Examples of urban infrastructure for urban heat mitigation: (a) white (reflective) infrastructure: white roofs, white walls, and white pavements, (b) green (vegetation) infrastructure: urban lawns, green roofs, and green walls, and (c) blue (waterscape) infrastructure: pools, lakes, and rivers.

The denomination of white infrastructure here refers to engineering materials highly reflective to solar radiation that appear white in color, including white roofs, walls, and pavements, as shown Fig. 1a. The use of white infrastructure for heat mitigation has been extensively studied in the literature; interested readers are referred to specific reviews in this field for details (see, e.g. Akbari et al., 2012; Qin, 2015; Santamouris and Yun, 2020). It is noteworthy that the phrase "cool" has been widely used as the synonym of "white" in the literature (e.g. cool roofs). In this category, we may also associate with the use of other innovative engineering materials for heat mitigation, such as phase change materials (Nagano et al., 2004; Roman et al., 2016), retro-reflective coating (Rossi et al., 2016; Yuan et al., 2016; Manni et al., 2020), permeable/porous pavements (Stempihar et al., 2012; Liu et al., 2018; Ferrari et al., 2020), etc., sometimes broadly labeled as the *grey* infrastructure. The primary mechanism underlying the white (or grey) infrastructure for heat mitigation is by changing the thermal material properties of urban surfaces especially the building envelops. The high surface albedo of reflective materials helps to sending more direct shortwave (solar) radiation back to the atmosphere, hence reduces the net available energy impinged on urban surfaces. Phase change and permeable materials, on the other hand, helps to retard heating of paved surfaces by converting available energy to the latent heat of phase transition or by quicker heat dissipation.

As alternative to the use of engineering materials, urban greening is another effective and popular means for heat mitigation (Bowler et al., 2010; Shashua-Bar et al., 2011; Vijayaraghavan, 2016; Besir & Cuce, 2018; Koch et al., 2020). Commonly used urban green infrastructure for heat mitigation include urban lawns, shade trees, green roofs, and green walls (Fig. 1b). Other forms of green infrastructure include rooftop gardens, parks, urban agriculture, urban forests, etc. Urban vegetation at the ground level can be further classified into two sub-categories, viz. mesic and xeric landscapes. A well-maintained grassland (lawns, gold courses, parks, etc.) with ample irrigation features a typical mesic landscape that is highly water demanding. The cooling effect of a mesic landscapes is a result of re-partitioning of sensible and latent heat, viz. more available energy impinged on urban surfaces will be used to vaporize liquid water through evapotranspiration instead of heating urban surfaces and the atmosphere; and its efficacy requires high heat-water trade-offs (Yang & Wang, 2015; C. Wang et al., 2019a). In contrast, xeric landscapes are often found in arid or semi-arid cities with native (often water-saving) species of trees or shrublands, with radiative shading as the primary mechanism of cooling (Upreti et al., 2017; C. Wang et al., 2018a, 2019b). In addition to the ground-level urban vegetation, greening of the urban envelops (roofs and walls) is another popular form of green infrastructure, with cooling provided by evapotranspiration and additional layers of insulation (Alexandria & Jones, 2008; Sun et al., 2013; Cameron et al., 2014; Malys et al., 2014; Yang & Wang, 2014; Yang et al., 2016a; Coma et al., 2017).

In comparison to white and green infrastructure, the use of urban blue infrastructure (waterscapes) remains a relatively underexplored field and its impact on heat mitigation has been studied only till very recently (Steeneveld et al. 2014; Zuvela-Aloise et al., 2016; Broadbent et al., 2019; C.Y. Wu et al., 2019; Fung and Jim, 2020; Lin et al., 2020). Commonly included in the category of blue infrastructure are open waters such as pools, lakes, and rivers (Fig. 1c). The use of blue infrastructure, like green infrastructure, was originally designed as urban landscape planning strategies for stormwater management. The two are commonly combined as green-blue infrastructure (GBI) in the landscape management literature and have the natural co-benefit of flood control in addition to environmental cooling (Perini and Sabbion, 2016; Alves et al., 2019, 2020; Kapetas and Fenner, 2020). The presence of a waterscape in a metropolitan and its cooling of the ambient environment usually manifest as an *oasis* in the built environment during daytime

(Fan et al., 2017), while the heat capacity of water makes it warm during nighttime (Steeneveld et al. 2014).

This paper is not intended to be an exhaustive review of urban mitigation strategies, but rather a critical evaluation of the *compound* environmental impact of heat mitigation strategies on ambient temperature, air quality, building energy efficiency, human well-being and health, and other ecosystem services. Given the excessively voluminous literature on urban heat mitigation strategies, the selected studies in this review are limited to publications after Year 2000, with the focus on compound (multiple) environmental measures rather than on a singular (especially cooling) effect alone. This synthetic effort is expected to help promoting the integration of urban mitigation strategies into the context of a holistic framework of general urban liveability inclusive of issues such as air quality, energy-water-climate repercussions, and diverse ecosystem services (Howells et al., 213; Antognelli et al., 2016; Simpson and Parker, 2018; Martinez-Bravo et al., 2019).

The rest of the paper is organized as follows. The *co-benefit* of urban mitigation strategies are reviewed and discussed in Section 2, with subsections focused on the compound effect of cooling and building energy saving (Section 2.1), air quality (Section 2.2), carbon emission (Section 2.3), and health impact (Section 2.4). It is followed by review and discussion of critical *trade-offs* using common urban mitigation strategies in Section 3, viz. the heating penalty of reflective surfaces (Section 3.1) and the heat-water trade-offs induced by urban irrigation (Section 3.2). We then proceed to illustrate in Section 4 the *unintended consequence* associated with urban mitigation strategies that should be avoided whenever possible. The use of urban mitigation strategies for conserving biodiversity and other ecosystem services is reviewed in

Section 5. We then venture to develop a theoretical framework for quantifying the compound environmental impact in Section 6 and present some concluding remarks in Section 7.

2. Environmental co-benefits of urban mitigation strategies

2.1. Compound effect of cooling and building energy saving

One immediate effect of urban heat mitigation is to reduce the energy use for cooling in hot days, via different pathways of re-partitioning of available energy impinged on urban surfaces and building facets. Results of cooling and building energy savings from studies on different heat mitigation strategies selected in the literature are summarized in Table 1. It can be seen that the quantitative results differ widely from case to case and depended heavily on local climatology, seasonality, characteristics of mitigation strategies, or even scales of numerical simulations. More specifically, it was reported that cool roofs are usually more effective in reducing heating load in hot seasons as compared to other techniques, but often lead to increase of heating load (aka *heating penalty*) during cold seasons (Zinzi and Agnoli, 2012; Virk et al., 2015; He et al., 2020; Berardi et al., 2020). In the extreme case, a “super-cool” rooftop with surface albedo greater than 0.96 is even capable of maintaining its surface temperature below the ambient air temperature throughout the year in all climates (Baniassadi et al., 2019).

In contrast, green roofs and walls provide additional layers of insulations (growing medium + plant canopy) to building envelops, which makes them capable of reducing both heating and cooling load in most weather conditions. However, the cooling efficacy of green roofs and walls bear complex relationship to many factors, including the growing medium, plant foliage, photosynthetically active radiation (PAR), irrigation, to name a few. Interested readers can found more detailed information in comprehensive reviews of the use of green roofs for heat mitigation for building energy saving (see e.g. Alexandria & Jones, 2008; Azkorra et al., 2015; Susca 2019; Koch et al., 2020).

Table 1. Summary of cooling and energy saving potentials of different urban heat mitigation strategies

Strategy	Methodology	Study area	Temperature reduction	Cooling energy saving	References
Cool surfaces & shade trees	DOE-2 building energy model	Multiple U.S. cities	N.A.	~20% nationwide	Akbari et al. (2001) Akbari & Konopachi (2005)
Green roofs	EnergyPlus	Chicago, IL Houston, TX	N.A.	2% electricity, 9%-11% natural gas	Sailor (2008)
Cool and Green roofs	EnergyPlus	Mediterranean region	10%-80% reduced 28°C+ hours	8%-17%	Zinzi & Agnoli (2012)
Cool roofs	Regression or field observation	Hyderabad, India	5.2 °C outdoor T_{air}	14%-26%	Xu et al. (2012)
Urban irrigation	Urban canopy model (UCM)	Phoenix, AZ, U.S.	~3 °C canyon T_{air}	\$1.19 per m^2 wall area	Yang & Wang (2015)
Green and cool roofs	ADMS T&H 4	London, U.K.	~1 °C $T_{air,max}$	18% cool roofs 23% green	Virk et al. (2015)
Lawns and trees	UCM	Phoenix, AZ, U.S.	2.4 °C (lawn), 5.5 °C (trees) $T_{air,\ max}$	\$1.82/m^2 or \$5.50/m^2 for max lawn/tree	Z. H. Wang et al. (2016)
Green roofs	ENVI-met + EnergyPlus	Toronto, ON, Canada	0.4 °C T_{air}	3%	Berardi (2016)
Urban trees	EnergyPlus	Nanjing city, China	0.3-3 °C ambient T_{air}	12.4%-15.2%	Hsieh et al. (2018)
Common greenery	ENV-met	Hong Kong	3.3-5 °C PET (30% greenery coverage ratio)	1900-3000 kWh per summer day per 500×500 m^2	Morakinyo et al. (2018)
Cool pavements	ENVI-met + EnergyPlus	Thessaloniki, Greece	< 0.2 °C in monthly mean T_{air}	< 1.5%	Tsoka et al. (2019)
Green walls	ENVI-met	Chenzhou, Hunan, China	2610-8267 W cooling power	6.29%-19.92%	J.Y. Li et al. (2019)
Thermochromic coatings	Laboratory + simulations	Toronto, ON, Canada	15-20 °C skin temperature	8.9%	Berardi et al. (2020)
Cool and green roofs	THERB + hygrothermal transfer	Shanghai, China	3.3 °C (cool roofs), 2.9 °C (green roofs)	3.6%	He et al. (2020)
High albedo surfaces	WRF-BEP + BEM	Toronto, ON, Canada	3.3 °C daily average $T_{surface}$	10%	Jandaghian & Berardi (2020)
Reflective surfaces + greenery	Combined miscellaneous methods	Sydney, Australia	2.9 °C peak ambient temperature	80% overheating reduction	Santamouris et al. (2020)

Urban green space at the ground level, e.g. mesic lawns or xeric trees, have different pathways of cooling and building energy saving. Mesic lawns or grasslands are roughly planar (two-dimensional) and help to reduce the building cooling load rather indirectly by cooling the ambient air in street canyons. Xeriscaping with shade trees, on the contrary, have three-dimensional (3D) morphology and can provide cooling via direct shading by shielding off solar radiation from walls and roofs. As a result, urban trees are usually more effective and economic in promoting building energy efficiency as compared to lawns or shrublands lacking shading (Z. H. Wang et al., 2016). Likewise, it was also found that the use of cool pavements at the ground level induced insignificant cooling and energy saving in buildings (Tsoka et al., 2019). This is understood as reflective pavements do not directly transport heat to adjacent buildings, but instead reflect short- or long-wave radiations to walls (Wang, 2014; Yang et al., 2016b), which in turn can cause other unintended consequence (detailed in Section 4).

2.2. Environmental co-benefit of improving thermal and air quality

Most studies on the co-benefit of urban cooling and air quality improvement focused on the green infrastructure (Abhijith et al., 2017; Jones et al., 2019; Van Ryswyk et al., 2019). It is noteworthy that urban areas usually furnish favorable conditions for plant growth, because: 1) the elevated temperature in cities allows plants to maintain a higher photosynthesis rate and a longer growing period (Lahr et al., 2018; Meng et al., 2020; Zhao et al., 2016); 2) regular maintenance practices, such as irrigation and fertilization, relieve much of environmental stresses for plant growth (Luketich et al., 2019); and 3) the elevated CO_2 level forms a natural CO_2 pump, promoting the carbon assimilation and plant growth rate (H. Wang et al., 2017; S. Wang et al., 2019). Due to their peculiar growing conditions in the built environment, urban vegetation behaves distinctively from plants in the natural environment with different physiological functions (Calfapietra et al., 2015).

Concerning air quality in urban areas, particulate matter (PM) and ozone (O_3) are two well-characterized air pollutants as regulated by the U.S. Environmental Protection Agency (EPA, 2013, 2019). Nitrogen oxides (NO_x) and volatile organic compounds (VOC) have also been extensively studied in the urban environment, especially as ozone precursors. Studying the co-benefit of urban greening for heat mitigation and air quality improvement have attracted much research effort in the past decades. In general, strategic placement of vegetation in cities can contribute to the improvement of air quality by reducing average concentrations or fluxes of emission of criteria air pollutants (e.g. Pugh et al., 2012; Ren et al., 2017; Rafael et al., 2018; de Jalon et al., 2019; Y. Q. Zhang et al., 2020), and negative air ions or bacteria rate (Zhu et al.., 2017). There are two major pathways for improving air quality using urban vegetation: (1) the direct effect of removing pollutants through deposition (Janhall, 2015; Sicard et al., 2018; L. Wang, 2018; de Jalon et al., 2019), and (2) the indirect effect of lowering pollutant concentration by cooling the environment, albeit via complex temperature-dependent (e.g. stomatal, enzymatic, etc.) mechanisms of secondary formation (Fallmann et al., 2016; Lun et al., 2020; J.L. Zhang et al., 2020). More quantitively, for instance, Pugh et al. (2012) showed that increasing deposition by urban greening can reduce street level concentrations in street canyons by as much as 40% for NO_2 and 60% for PM, respectively. Y. Q. Zhang et al. (2020) predicted that the implementation of urban green infrastructure decreased the average and hourly maximum ozone concentrations by 0.9 and 1.4 ppbv respectively, over the downtown areas of Kansas City during summertime.

It is noteworthy that among different forms of urban vegetation, trees are found to be more effective than lawns or green roofs for regulating air quality (Jayasooriya et al., 2017). This advantage can be attributed to the 3D morphology of trees as compared to the planar (2D) form grasslands with similar physiological functions; the same reason is responsible for the advantage of urban trees in building energy saving (see Section 2.1). In particular, it was found that urban trees, most noticeably *coniferous* forests, can effectively remove both PM and ozone by dry deposition, with roughly equal efficacy in the Basque Country (de Jalon et al., 2019). This is worth noting because coniferous trees, especially the native species, is especially fitful for cities in semiarid and arid environment facing the *double evil* of UHI and water scarcity as to optimize the heat-water trade-off (detailed in Section 3.1).

Furthermore, we highlight some important considerations for optimizing the co-benefit of ameliorating thermal and air quality by urban greening, as revealed from the literature review:

(1) Context dependency: The impact of urban green space on air quality is highly context dependent, meaning that plants can improve urban air quality when strategically planned, but can be ineffective or even detrimental in other cases (Vos et al., 2013; Hewitt et al., 2020; Wang, 2020). Specifically, the mechanisms governing the interplay between thermal environment and air quality are strongly regulated by urban landscape dynamics and temperature-dependent (Camalier et al., 2007; C. Wang et al., 2017; Chen et al., 2019; Lun et al., 2020).

(2) In-canyon flow physics: One major factor that regulates the aforementioned context dependency is the peculiar characteristics of urban flow (Fernando, 2010). In particular, the presence of trees in street canyons alters the flow and physics of scalar transport in urban canyons, depending on the canyon and tree morphology (Amorim et al., 2013; Gromke and Blocken, 2015; Li and Wang, 2018). As a result, e.g. it was found that trees with high leaf area density are beneficial to reducing pollutant concentration in wide street canyons, while trapping

of pollutants is manifest in narrow canyons under skimming flow and splitting of vortices by trees (C. Wang, et al., 2018b).

(3) Plant species: The co-benefit of mitigating heat and air pollution also depends heavily on the selection and diversity of plant species. For example, J. L. Zhang et al. (2020) found that the uptake rate of NO_x can be significantly increased by selecting a specific tree species, *Alnus glutinosa* which remains resilient to future climate changes. Furthermore, research suggested that species richness amounts to the best biodiversity metric for measuring the efficacy of urban green space on ameliorating air quality (Matos et al., 2019).

(4) Planetary boundary layer (PBL) dynamics: The compound effect of urban cooling and air quality also involves complex land-atmosphere interactions and the thermodynamic characteristics of the overlying atmospheric boundary layer (Song and Wang, 2015a,2016a). In general, the cooling of urban surfaces and the canopy layer induced by urban mitigation strategies leads to a lower planetary boundary layer (PBL) height (Song & Wang, 2015b, 2016b; Song et al., 2018), which in turn changes the atmospheric concentration of pollutants and the pathways of secondary formation (Y. H. Wu et al., 2019; Y. Q. Zhang et al., 2020).

(5) Nonlinear effect: the transport and fate of air pollutants do not generally bear monotonic or linear correlation with emission sources, plant phenology, or photochemistry of precursors (Xiao et al., 2010; Xing et al., 2011; Xie et al., 2014; Jochner et al., 2016; Hong, 2017). Furthermore, determinants of air pollution in urban areas often involve competing mechanisms that operate simultaneously. One particular challenge realized by researchers is the relationship between ozone and biogenic volatile organic compound (BVOC). For example, Xiao et al. (2010), using photochemical modeling, identified that daytime ozone exhibits nonlinear responsiveness to precursor (NO_x and BVOC) emissions. As a result of this intense nonlinearity,

moderate perturbations (10-30%) in either precursor emissions inventories could qualitatively flip the model results. In the presence of urban trees, the nonlinear interactions between ozone and BVOC renders it particularly challenging to accurately estimate the ozone level at urban scales (Calfapietra et al., 2013).

In comparison to urban greening, research effort on the impact of reflective materials on urban air quality remains relatively scarce up to date. Existing studies suggested that, based on numerical simulations, the use cool roofs or walls gave rise to air quality penalty in terms of increase of $PM_{2.5}$ level, while its impact on ozone level remains divergent (Epstein et al., 2017; Zhang et al., 2019). The penalty is supposedly due to the reductions in ventilation associated with surface cooling. It is interesting to note that a recent study by Han et al. (2020) showed that cool roofs led to decreased near surface O_3 concentration in Seoul due to weakened sea breeze that brings high ozone concentration air flows into the city. This apparent benefit of cool roofs on ozone air quality is quite peculiar and precarious to extend to other metropolitan areas, as the ozone concentration generally decreases over the urbanization gradient (Strosnider et al. 2017) and reduced urban-rural breeze tends to generate higher ozone level accumulated in urban cores. Overall, it remains hitherto a big knowledge gap and much more field observations and numerical simulations are needed in the future for in-depth understanding of potential co-benefits, trade-offs, or unintended consequence of white infrastructure with respect to air quality.

2.3. Co-benefit of heat and carbon mitigation

Urban areas are hotspots of carbon emission, especially the anthropogenic CO_2 ($AnCO_2$) (Grimmond et al., 2002; Pataki et al., 2006; Hutyra et al., 2014). Cities contribute ~70% of $AnCO_2$ emissions mainly through fossil fuel burning (UN-Habitat, 2011; Churkina, 2016), which constitutes the largest carbon flux to the atmosphere and represents the dominant source of GHG forcing to emergent climate patterns (Gurney. 2014). More specifically, complex heat-carbon interactions are responsible for the co-evolution of thermal and carbon dynamics in the built environment (Balling et al., 2001; Vetter et al., 2008; Wang, 2020). For example, it was found that emission rates of biogenic and anthropogenic CO_2 increase under high ambient temperature (Churkina et al., 2017; Humborg et al., 2019). The elevated CO_2 concentration, in turn, tend to exacerbate the local thermal environment and contribute to the longterm trend of urban warming (Hutyra et al., 2014, Churkina, 2016). The inverted trend, i.e. reduction of $AnCO_2$ emission by urban mitigation strategies, therefore has the potential to check the warming trend of global climate changes in the long run (IPCC, 2014).

For reflective (cool) surfaces, Akbari et al. (2009) came up with a simple proportionality of 0.01 albedo increase to offset 2.55 kg CO_2 (or 7 kg in Akbari et al., 2012) per square meter of urban area, based on the rational that the increase of albedo in urban areas can be equivalent to the reduction of atmospheric CO_2 emission since both leading to the change of radiative forcing. Using this proportionality, it was estimated that a global increase of net urban albedo of about 0.1 can lead to a negative radiative forcing on the earth equivalent to offsetting about 44 Gt of CO_2 emissions (Akbari et al., 2009). A higher estimate of global offset 57 Gt of CO_2 emissions was reported by plausible increases of surface albedo of 0.25 (roof) and 0.15 (pavement) (Menon et al., 2010). Nevertheless, these lumped proportionality between cooling and CO_2 offset is apparently an over-simplification to the complex interactions of carbon dynamics and radiative forcing as well as the climate response (Good et al., 2015).

Similar to the treatment with cool surfaces, Lin et al. (2011) estimated the carbon saving as a result of cooling effect of urban green space. Remote sensing imagery (Landsat-ETM) were used to identify the cooled areas, where possible energy use to maintain the temperature differences between cooled areas and their warmer surroundings was estimated, followed by the calculation of the carbon savings owing to the avoidance of energy use. Recently, it has been pointed out that the use of lumped correlation between the static average CO_2 saving and building energy efficiency could be misleading and lead to inaccurate estimation (Pylsy et al., 2020).

Weissert et al (2014) conducted a review on the influence of urban forests to mitigate CO_2, whereas the quantification of dynamic interactions of urban trees with the built environment in carbon exchange processes was at its infancy at that time. There has long been a lack of accurate estimation and prediction of the co-benefit of heat and CO_2 mitigation by urban greening due to the lack of sophisticated modeling techniques. Physically-based numerical models capable of integrating realistic land surface processes and urban carbon dynamics were only developed recently (Goret et al., 2019; Li and Wang, 2020, 2021a). Enabled by the new tools, it was found that expanding urban green space resulted in the environmental co-benefit of reducing heat and CO_2 emission; the efficacy varies for different vegetation types (Li and Wang, 2021b).

2.4. Health impact of heat mitigation

Degradation of environmental quality, especially the presence of elevated temperature and air pollution, impose serious threat to human well-being and public health (Mishra and Ramgopal, 2013; USGCRP, 2016), which increases the risk of morbidity and mortality in urban areas (McMichael et al., 2008; Tan et al., 2010; Gabriel & Endlicher, 2011; Rosenthal et al., 2014). The health impact is more severe for sensitive segments of the population, including the elderly, children, and low-income individuals (Patz et al., 2005; USGCRP, 2016). In this section, we provide an overview of the co-benefit of urban mitigation strategies with implications to health of urban residents and improvement of the urban liveability in general.

The primary health benefit of urban mitigation strategies is to reduce morbidity and mortality associated via two major pathways, viz. (a) cooling and thermal stress alleviation (Burkart et al., 2016; Salata et al., 2017; Chan et al., 2017; Park et al., 2020; Venter, et al., 2020) and/or (b) improving of air quality (Cifuentes et al., 2001; Jack and Kinney, 2010; Ramaswami et al., 2017; Ren et al., 2017). For example, a recent study showed that a combination of reflective surfaces, additional greenery and other mitigation strategies, was capable of reducing the heat-related morbidity by 1.07-1.49 and the heat-related mortality anomaly by 1.39 per 100,000 citizens in Greater Sydney, Australia (Santamouris et al., 2020).

Results from case studies also showed that urban plants, help to human well-being and public health by pollutant removal (Jack and Kinney, 2010; Zhao et al., 2013; Nowak et al., 2018, 2019; Arantes et al., 2019). In particular, there is an emerging research area that looks into the impact of urban green space, especially trees, on the respiratory-related health problems, such as asthma (Lovasi et al., 2008; Eisenman et al., 2019; Aerts et al., 2020). Up to date, the complex causal pathways between urban greening, air quality, and health remain obscure (Eisenman et al., 2019).

In addition, urban greenery has the recreational and aesthetic co-benefits to urban residents, which helps to improve their visual comfort, though different demographic groups differ in their preference of specific vegetated landscapes (Chen et al., 2015; Du et al., 2016; R.G. Wang and Zhao, 2017). In addition, urban green space can serve as a physical and psychological buffer for the negative health impact by noise reduction (Dzhambov and Dimitrova, 2014; Azkorra et al., 2015; Sakieh et al., 2017), promote the combined restorative auditory-visual potentials (Zhao et al., 2018; Deng et al., 2020), improve mental health and well-being in general (Andreucci et al., 2019, Andersson et al., 2019).

3. Trade-offs in urban mitigation strategies

The review of the environmental co-benefits of urban mitigation strategies in Section 2 has already given us some inkling of their trade-offs, or more plainly, the price necessary to purchase the desired co-benefit. In this section, we will give an in-depth review two particular trade-offs, viz. heating penalty of reflective surfaces and heat-water nexus of urban irrigation, and their potential remedies or implications.

3.1. Heating penalty

The problem of heating penalty associated with the use of reflective surfaces is quite intuitive: white surfaces reflects more solar radiation back to the atmosphere than conventional grey pavements, hence lower the surface (skin) temperature of the paved surfaces regardless of the weather conditions. This all-weather cooling effect leads to the increase of heating energy consumption in cities located in temperate to cold climate regions during winters, a *penalty* or rather a trade-off necessary to gain building cool energy saving during hot seasons. To decide whether or not reflective pavements should be used as heat mitigation strategy therefore depends on the *net* building energy saving. It follows intuitively that for cities located in heating-dominated climates, the use of cool roofs can result in a net energy loss due to the heating penalty (e.g. London, see Virk et al., 2015). A simple rule of thumb is that the summer cooling saving by cool surfaces can be roughly balanced by the winter heating penalties in climate regions with less than 1000 cooling-degree-days (Akbari and Konopachi, 2005). The case is more complicated when retro-reflective materials are used for building coating, which can generate uneven redistribution of solar energy, leading to cooling and heating on different urban canyon facades (Manni et al., 2020).

One way to remedy the heating penalty generated by reflective surfaces is to use vegetated building envelops instead of white roofs or walls. Green roofs or vertical walls provide additional layers of insulation by growing medium and plant canopy, which can even save heating load in winters as confirmed by numerous studies (see, e.g. Zinzi & Agnoli, 2012; He et al., 2020). It is worth noting an alternative remedy, perhaps singular in the literature, is to use different roof coatings during different seasons, i.e. white in the summer and black in the winter. Ramamurthy et al. (2014) investigated this potential solution using numerical simulations applied to Princeton, NJ by an urban canopy model (Wang et al., 2013). The real challenge of this seemingly simplistic, but potentially promising, engineering approach lies with the design and production of innovative pavement materials capable of color changing with response to different intensity of solar (e.g. ultraviolet) radiation.

3.2. Heat-water trade-off for urban irrigation

The use of urban vegetation for heat mitigation is naturally supplemented by urban irrigation, especially for cities in arid or semiarid regions. Yang and Wang (2015) evaluated different urban irrigation schemes for achieving optimal heat-water trade-offs using a single-layer urban canopy model (UCM). It was found that in Phoenix metropolitan, the best strategy is for urban irrigation to be activated by urban temperature. Using a mesoscale regional climate modeling, it was found that in Phoenix, AZ, the urban irrigation would amount to five times the current irrigation water use for an oasis (fully green) city with a urban cooling of 2~2.5 ºC (air temperature) (Yang and Wang, 2017). In contrast, a complete desert city is capable of saving 77 ± 5 Mm^3 of irrigation water in the summer (June, July, August) over the entire Phoenix metropolitan area by suffering ~1 °C warming of urban air temperature. This amounts to about 240 mm (per unit area) of irrigation water for three summer months, which is comparable to an earlier estimate of the usage of ~135 mm (per unit area) of irrigation for a nocturnal cooling rate of 0.6 – 1.4 °C/hour in the same metropolitan area (Gober et al., 2010).

This heat-water trade-off, or as Gober et al. (2010) nicely phrased it as "how much water will it take to cool Phoenix?", lately leads to a the development of a convenient measure of *urban water capacity*, analogous to heat capacity in thermodynamics, to denote the amount of average irrigation (water) depth to effectuate one degree of temperature reduction (C. Wang et al. 2019a). The values of urban water capacity are found to be 4.52 ± 0.77 mm day^{-1} $°C^{-1}$ and 7.27 ± 1.27 mm day^{-1} $°C^{-1}$ for surface and near-surface air cooling respectively, for all urban areas over the contiguous United States (CONUS). In addition, in large metropolitan areas, urban cores with higher density of buildings and paved surfaces have better irrigation economy as compared to their peripheral suburban areas.

4. Unintended environmental consequence

In this section, we review the unintended environmental impact induced by implementation of white, green, and blue infrastructure for heat mitigation. While the trade-offs of urban mitigation strategies might be reckoned as a *necessary but lesser evil* to improve the overall environmental quality in urban areas, there unintended consequence, on the contrary, are the side effects that should be avoided whenever possible.

4.1. Reflective surfaces

Yang et al. (2015) conducted a comprehensive review of the unintended consequence of cool roofs and cool pavements. Besides the heating penalty already discussed in Section 3.1 above, the unintended consequence includes the adverse impact on the thermal environment of urban peripheries, regional hydroclimate, and air quality, as well as potential safety or health issues. Here we only review more recent studies (published after Yang et al., 2015) on the adverse environmental impact arising from reflective surfaces.

Sharma et al. (2016) evaluated the impact of cool roofs on the regional hydroclimate using high-resolution (1 km) Weather Research & Forecasting (WRF) model. It was found that reflective roofs (as well as green roofs) led to reduced wind speeds and vertical mixing and lower PBL height, which in turn caused stagnation of air near the surface that can potentially impede the dilution or dispersion of pollutants and causing degraded air quality in urban areas. More specifically, large-scale deployment of cool roofs and cool walls gave rise to air quality penalty in terms of increase of urban ozone and PM levels, attributable to the reductions in ventilation associated with surface cooling (Epstein et al., 2017; Zhang et al., 2019). It is therefore urged that the implementation of reflective surfaces should carefully take into consideration of the competing feedbacks between cooling and PBL dynamics.

As for the potential hazard to human safety or health imposed by reflective surfaces, it was reported that cool surfaces installed over pedestrian passage could produce some visual discomfort due to glare issue, according to a field survey (Rosso et al., 2016). The optical behavior of reflective pavements also affected the uniformity of visions for drivers and required ad-hoc installation of additional light sources (Rossi et al., 2018).

4.2. Green and blue infrastructure

As reviewed in Section 2.2, the use of urban green space to improve air quality requires careful selection of plant species and strategic planning of locations, which needs to be informed by detailed analysis of simulation-based results. Nevertheless, the intricate balance between cooling and air quality improvement can be easily tipped, leading to unintended consequence often unfavorable to urban air quality. For example, a recent study showed that the implementation of green infrastructure caused an approximately 10% increases in summertime $PM_{2.5}$ mostly during nighttime in Kansas City (Y. Q. Zhang et al., 2020).

The primary causal pathway, engendering the adverse impact of urban trees on air quality, has been identified as the air flow modification by tree morphology and leaf area density, which generates the blocking effect or reduced ventilation for pollutant dispersion (Vos et al., 2013; C. Wang et al., 2018b; Rui et al., 2019). On top of that, the reduced PBL height due to surface cooling via urban land-atmosphere interactions (Song and Wang, 2015a, 2016a) tends to increase the atmospheric concentration of pollutants. To add the geographic nuance, it was found that urban trees in cool climate can increase carbon emissions from residential building energy use due to undesirable shading in cold seasons (Erker and Townsend, 2019) (c.f. the heating penalty by reflective surfaces as discussed in Section 3.1).

Furthermore, urban areas are more susceptible to severely degraded air quality during heat extremes. During extreme heatwaves, high emissions or mixing ratios were observed for ozone, $PM_{2.5}$, BVOC, and CO_2 (Churkina et al., 2017; Humborg et al., 2019; Y. H. Wu et al., 2019; Zhao et al., 2019). In particular, the excessive BVOC (the major precursor to ozone) emission by urban trees, especially during extreme heat (Churkina et al., 2017), can lead to severe ozone pollution and detrimental health impact. For instance, Ren et al. (2017) found that urban trees, in comparison to rural forests, played much more important roles in threating human health via BVOC emissions, which amounted for 62% of total health damage. The rate of BVOC emission varies significantly across different plant species, which can potentially offset the biogenic carbon uptake and/or pollutant deposition, and tip the balance from co-benefit to trade-off between the urban cooling and air quality improvement. It is therefore of critical importance for urban planners to carefully select plant species and take into consideration the potential trade-off between air pollution removal and survival probability (J. L. Zhang, 2020), especially in the context of future climate change.

Unintended consequence was also identified with respect to irrigation, an integral component of green infrastructure. Large-scale irrigation for agricultural or urban plant use has the potential to induce long-range impact on regional to global scale hydroclimate (Puma and Cook, 2010; de Vrese et al., 2016), hence increases the uncertainty of future climate projections. Irrigation also increases atmospheric humidity through evapotranspiration, which, in combination with high temperature, enhances the intensity of extreme heatwaves. This synergistic effect, as illustrated by Kang and Eltahir (2018), would generate deadly heatwaves with wet-bulb temperature exceeding the threshold tolerable to human bodies and threaten the entire North China Plain under projected climate changes.

The function of blue infrastructure (waterscape) in urban areas bears much similarity to irrigation with ample supply of surface water for cooling the environment. Analogous to the intensification of heatwaves by irrigation, Steeneveld et al. (2014) found that the presence of water bodies increased the UHI intensity. This is because the diurnal and annual cycles over water are suppressed due to high heat capacity, and water temperatures remain relatively high even after nocturnal or seasonal transitions. Nevertheless, due to the dearth of research effort on blue infrastructure, our understanding of its unintended consequence to the built environment still remains primitive up to date.

5. Biodiversity and ecosystem services

By far we have reviewed and discussed the major compound environmental impact of urban mitigation strategies in terms of building energy efficiency, urban air quality, carbon emissions, and health impact. In this section, we review the *secondary* influence by various heat mitigation techniques for conserving biodiversity and supporting ecosystem services in the built environment. It is understood that by secondary, we do not intend to downplay the importance of the ecosystem services reviewed below, but rather to signal the fact that they are relatively under-explored, and to encourage future research endeavor to broader the research frontier in this challenging (highly transdisciplinary in nature) but promising field.

We have mentioned (Section 2.2) that cities furnish peculiar growing conditions to urban plants. In addition, the implementation of new urban mitigation strategies has profound and far-reaching impact on the native flora and fauna by: (1) changing their native habitats, (2) directly introducing alien and potentially invasive species of plants, insects, birds, etc., and (3) creating new environmental stressors. In particular, the living and growing conditions of native urban species have jeopardized due to the loss of habitats (Maskell et al., 2006; Menke et al., 2010; Kozlowski & Bondalla, 2013; Wells et al., 2014), invaded and outgrown by alien species (Ruthrof et al., 2003; Lososova et al., 2012; Le Louarn et al., 2018; Clements et al., 2019), fall prey to urban ecological traps (Stracey & Robinson, 2012). It is critical for conserving urban biodiversity by conserving the native flora and fauna and facilitating their symbiosis with alien species under the changing urban environment and habitat structure is critical (Garden et al., 2007; 2010; Threlfall et al., 2015; Tordoni et al., 2017).

Hence it is rather exciting to find that recent studies revealed that urban green space can provide complementary and protective habitat to native and endangered species, especially with their transpiration and cool potentials (Pan et al., 2019; Tan et al., 2020; Gastreich & Presler, 2020). By analogy, we anticipate that urban waterscape should be capable of providing similar co-benefit of cooling and biodiversity conservation to aquatic species, though the research effort is hitherto lacking. It also remains to be explored how the use of white infrastructure can impact the native species and their habitat in the urban environment. In the light of the adverse impact exerted by reflective surfaces on human health and safety (Section 4.1), it will not be completely groundless to speculate there might be some unintended consequence to ecosystem services by large-scale implementation of white infrastructure.

A new paradigm is needed for future research to explore the compound environmental impact of urban mitigation strategies in supporting urban ecosystem services. Pioneering work has been conducted to investigate the integrated ecosystem services of GBI with multiple objectives inclusive of pollutant reduction, biodiversity, and ecosystem conditions (Barbosa et al., 2019; Strain et al., 2019). In particular, Barbosa et al. (2019) proposed a framework for systematically selecting cost-effective areas for optimizing the GBI design that addressed different conservation, restoration and exploitation objectives.

6. A unified framework for measuring the compound environmental impact

Speaking of the need of a new paradigm for future study of the compound environmental impact, here denoted as *CEI*, in this section, we venture to develop a mathematical framework for unified quantification of *CEI*, supplemented with some preliminary analysis as proof-of-concept. Our framework of generalization begins by considering a multivariate *impact space* of environmental measures $\mathbf{M} = \{M_i | i = 1, 2, 3, \ldots, n\}$ and a *coordinate space* of mitigation strategies $\mathbf{S} = \{S_j | j = 1, 2, 3, \ldots, m\}$, where each M_i denotes a singular measure of environmental impact (e.g. temperature, building energy consumption, pollutant concentration, morbidity or mortality rate, etc.), and S_{ij} denote individual mitigation strategies (see Fig. 1) quantifiable as changes of albedo, fractions of green space, irrigation amount, etc. A scalar measure of *CEI* can then be constructed, rather intuitively, as weighted average of *fractional changes* in the ensemble of M_i determined as specific urban planning objectives,

$$CEI = \sum_{i=1}^{n} w_i \delta \overline{M}_i , \tag{1}$$

where $\delta \overline{M}_i = \left(M_i - M_{\text{ref}} \right) / M_{\text{ref}}$ is the normalized (dimensionless) variation of the individual measure M_i, each associated with a weight w_i, and the subscript "ref" denotes the reference environmental state (not necessarily urban). Note that if we set $M_i = T_{\text{urban}}$ and $M_{\text{ref}} = T_{\text{rural}}$ as the ambient temperature in an urban area and its rural surroundings, we then recover the familiar measure $\delta M_i = T_{\text{u-r}} = T_{\text{urban}} - T_{\text{rural}}$, viz. the UHI intensity. The obvious advantage of normalizing individual measures, in the definition of compound environmental impact *CEI*, is to make different measures dimensionless and comparable. The choice of weight depends on the policy priority or credit assigned to individual indicators or objectives (e.g. improvement of air quality or saving of building energy) by urban planners, and should obey $\sum_i w_i = 1$.

Next, we assume that the scalar measure of *CEI* varies (adequately) smoothly over the entire coordinate space under the regional climate index *R*. This assumption allows us to analytically decompose and quantify the sensitivity of *CEI* to each relevant mitigation strategy separately, as

$$\delta CEI = \sum_{j=1}^{m} \frac{\partial CEI}{\partial S_j} \delta S_j + \Theta\left(M_i, S_j, R\right) = \sum_{j=1}^{m} \sum_{i=1}^{n} \frac{\partial w_i \delta \overline{M}_i}{\partial S_j} \delta S_j + \Theta\left(M_i, S_j, R\right), \tag{2}$$

where Θ represents the potential nonlinear (confounding or covariant) effect among variables in the coordinate and impact spaces subjected to regional climate changes. Examples of such nonlinearity include the temperature response to CO_2 concentration (Good et al., 2015), or partitioning of surface sensible and latent heat per Clausius-Clapeyron relation regulated by soil water availability (Yang et al., 2019). Alternatively, Eq. (2) can be written in matrix form as

$$\delta CEI = \sum_{i} \mathbf{J} \cdot \delta \mathbf{S} + \Theta, \tag{3}$$

where **J**: $\mathbb{R}^m \rightarrow \mathbb{R}^n$, with $J_{ij} = \frac{\partial w_i \delta \overline{M}_i}{\partial S_j}$ is the (weighted) Jacobian matrix. One exemplary element of the Jacobian matrix is the urban water capacity (C. Wang et al., 2019a) for measuring the heat-water trade-off as discussed in Section 3.2. Using the unified mathematical framework proposed above, the measure of urban water capacity can be derived as a specific element of the Jacobian matrix by taking M_i as the amount of irrigation water (in mm/day) and S_j as temperature (in ^{o}C).

The proposed mathematical framework, in particular the derivation of the Jacobian matrix, is further illustrated in Fig. 2 below. The procedure starts with the design of urban mitigation strategies in urban planning processes. The portfolio of scenarios, constitute of the coordinate space ***S***, are then assimilated as boundary conditions in the physically-based urban hydroclimate simulations, which in turn predicts the environmental response of the designed mitigation strategies. The Jacobian matrix is determined as the derivatives of the impact functions (e.g., cooling or CO_2 uptake) in response to the changes in landscape scenarios (e.g., albedo or vegetation fraction). Note that the Jacobian matrix admits spatio-temporal variabilities. Thus the quantification of *CEI*, for practical uses, needs to be spatially aggregated over the neighborhood/city of design or temporally averaged over the design period. The determined CEI can then be feedback to urban planners to inform their decision-making processes.

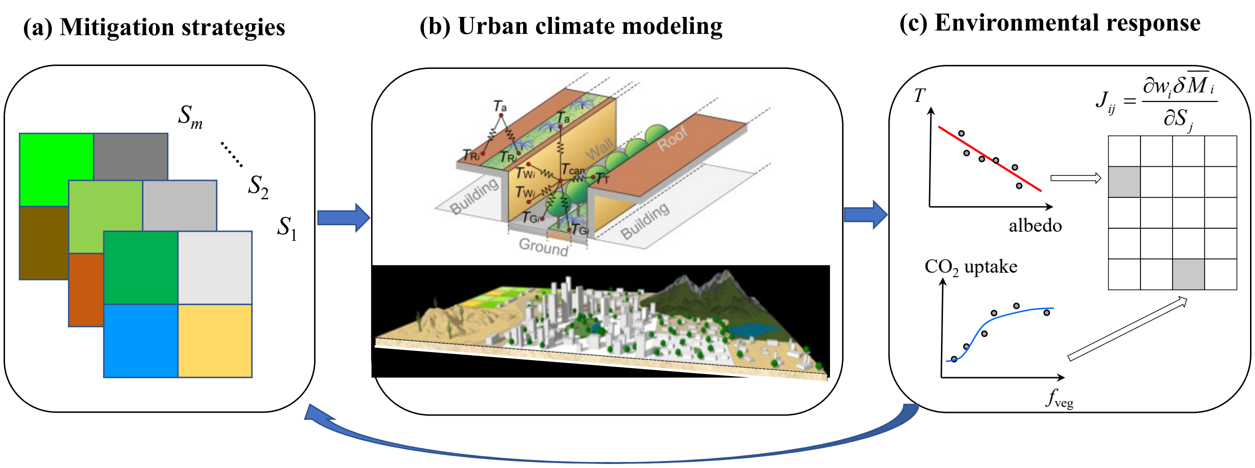

Figure 2. Illustration of the proposed mathematical framework: (a) design of mitigation strategies in urban planning, (b) local/regional urban hydroclimate modeling, and (c) quantification of environmental response and determination of the Jacobian matrix.

As a proof of concept, here we show the result of measuring the compound co-benefit of heat-CO_2 mitigation as a function of urban greening and irrigation, using a physically-based UCM-CO_2 model (Li and Wang, 2020). In this case, the coordinate space consists of two parameters $\{S_j|\ S_1 = \text{SWC},\ S_2 = f_V\}$ where SWC is the soil water content (due to irrigation), and f_V the vegetation fraction (due to urban greening); and the impact space is defined as $\{M_i|\ M_1 = T_{\text{can}},$ $M_2 = \text{NEE}\}$, where T_{can} is the canyon air temperature, and NEE the net ecosystem exchange (CO_2 flux). The results of numerical simulations are show in Fig. 3, where equal weight of 50% is assigned to NEE and temperature variations, and the nonlinearity in Eq. (2) is neglected for simplicity. It is clear from the graphs that: (1) urban greening supported with irrigation lead to a compound co-benefit of cooling and net carbon sink (Fig. 3a), and (2) the variation of CEI with respect to the vegetation fraction and soil moisture in the coordinate space is sufficiently smooth, which validates the assumption of our theoretical framework in Eq. (2) (Fig. 3b). It is also noteworthy that the slopes of the curved surface in Fig. 3b at a given point of the coordinate space correspond to the sensitivity of *CEI* with respect to different mitigation strategies.

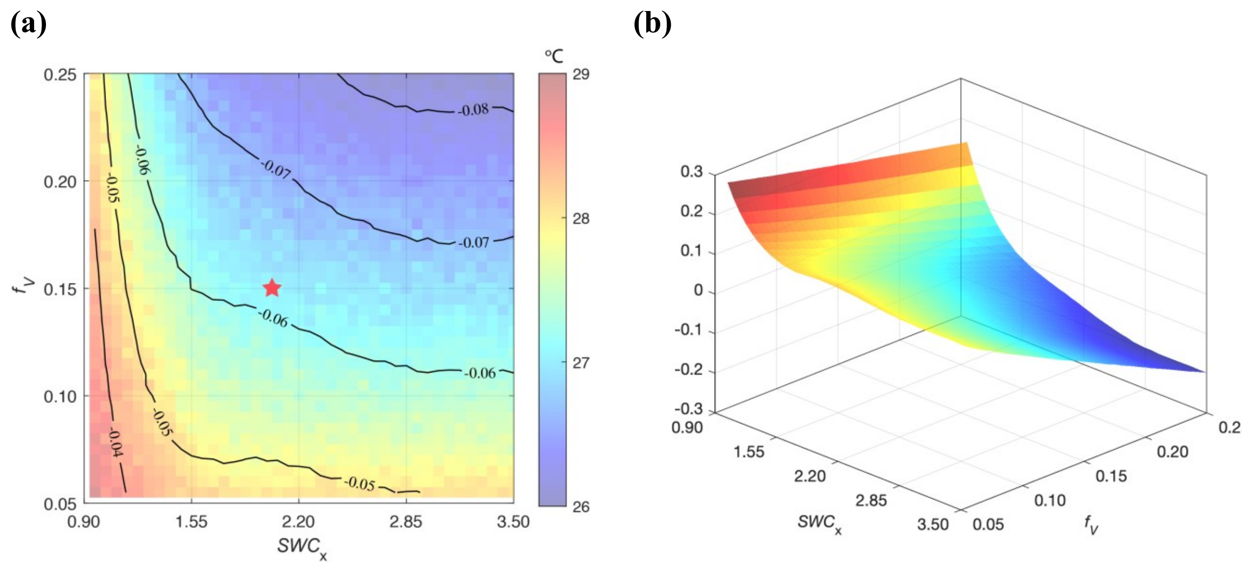

Figure 3. Compound co-benefit of heat-carbon mitigation using urban greening: (a) Simulated mean canyon air temperature (filled colormaps) and net ecosystem exchange (mg $m^{-2}s^{-1}$, contours, negative value signaling carbon *sink*), and (b) the scalar measure of *CEI*, as functions of vegetation fraction f_V and soil water content multiplier SWC_x, The star indicates the reference case. SWC_x is defined as the ratio of target soil moisture after irrigation to the measured monthly mean soil moisture at the site.

7. Concluding remarks

To summarize, we have critically reviewed the compound environmental impact of urban mitigation strategies and their potential or actual co-benefit, trade-offs, and unintended consequence in terms of impact on ambient temperatures, building energy consumption, air quality, carbon emission, human health, and biodiversity. In general, the major co-benefit of white infrastructure (reflective surfaces) consists of heat mitigation and saving of cooling load in hot seasons, whereas its heating penalty and potential adverse impact on air quality and human health need to carefully considered for large-scale implementation. In contrast, the use of urban green infrastructure is more versatile with far-reaching environmental impact on energy efficiency, air quality improvement, CO_2 offset, and positive impact on human health, ecosystem services and social equity. Among different forms of green infrastructure, urban trees are usually more effective in generating either positive co-benefit or negative consequence. Urban irrigation is essential to support the growth and physiological functions of plants, especially in arid or semiarid environment, but superfluous irrigation water use leads to marginal environmental benefit that is often negligible. The use of open waterscapes, or blue infrastructure, is relatively under-explored as compared to white or green infrastructure, and more future studies are needed to further our understanding to their compound environmental impact.

Furthermore, we can identify a number of knowledge gaps and outstanding challenges from this review. The major ones include: (1) The complex interplay between urban mitigation strategies and the urban carbon dynamics. This is particularly important in the context of global climate change as in current practice our projections of future climate rely heavily on the accurate prediction of future CO_2 concentration to which urban areas are the primary contributor. (2) The potential feedback mechanisms underlying the interactions between urban mitigation strategies and human behavior in the context of regional climate change. One interesting example is feedback between the use of air conditioning system and the UHI effect or heat extremes. (3) A systematic approach that integrates different urban land surface, hydrological, biochemical, and atmospheric processes in a unified framework for evaluating the compound environmental impact.

As a pioneering effort to address the last challenge, we propose a mathematical framework in this review. Preliminary analysis shows that this framework is capable of embracing the familiar environmental measures of urban mitigation strategies in the literature, including the conventional UHI intensity and urban water capacity. The results are promising for future research endeavor to quantify the compound environmental impact of reflective surfaces, urban green spaces, and open waterscapes in one unified framework.

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