The climate benefits, co-benefits, and trade-offs of green infrastructure: A systematic literature review

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Abstract:

Climate change increases risks to natural and human systems. Green infrastructure (GI) has been increasingly recognized as a promising nature-based solution for climate change adaptation, mitigation, and other societal objectives for sustainable development. Although the climate contribution of GI has been extensively addressed in the literature, the linkages between the climate benefits and associated co-benefits and trade-offs remain unclear. We systematically reviewed the evidence from 141 papers, focusing on their climate benefits, relevant co-benefits and trade-offs, and the GI types that provide such climate (co-)benefits. This study presents a comprehensive overview of the links between climate benefits, co-benefits and types of GI, categorized along a green-grey continuum so that researchers/practitioners can find information according to their topic of interest. We further provide an analysis of trade-offs between various GI benefits. 'Bundles' of major co-benefits and trade-offs for each climate benefit can be identified with recommendations for strategies to maximize benefits and minimize trade-offs. To promote climate-resilient pathways through GI, it is crucial for decision-makers to identify opportunities to deliver multiple ecosystem services and benefits while recognizing disservices and trade-offs that need to be avoided or managed.

Keywords: green infrastructure; climate change; adaptation; mitigation; co-benefits; trade-offs.

1.Introduction

Climate change is expected to increase risks for natural and human systems including heat waves, floods, droughts, and loss of biodiversity (IPCC, 2014). As urban areas are key contributors to greenhouse gas emissions (GHGs) as well as hotspots of the consequences, their climate responses play a critical role in limiting the global temperature increase to 1.5 °C above pre-industrial levels, in line with the Paris Agreement (Dale et al., 2019). Addressing the adverse impacts of climate change (adaptation) and reducing the causes of climate change (mitigation) are increasingly recognized as key challenges for sustainable urban development (Bai et al., 2010).

Although adaptation and mitigation are complementary for addressing climate change, they have been framed as two different actions within science and policy, and often discussed separately from the broader sustainable development agenda (e.g. Klein et al., 2005; Biesbroek et al., 2009). Recently, however, there is a growing awareness that integrated approaches can bring substantial synergies and co-benefits between adaptation, mitigation, and other societal objectives towards climate-resilient pathways for sustainable development (Swart and Raes, 2007; IPCC, 2014; Newell et al., 2018).

Implementing climate action with co-benefits through integrated approaches can result in "win-win" situations to society beyond mitigation and adaptation and increase the cost-effectiveness of measures (Laukkonen et al., 2009; Giordano, 2012). For example, strategies aimed at reducing GHGs emissions (e.g. increasing renewable energy provision) can lead to reductions in air pollution and the associated human health risks, while nature-based adaptation strategies to reduce coastal flood risks (e.g. coastal wetlands restoration) can result in improvements to habitats and local water quality (Berry et al., 2015). Despite these multiple benefits, some studies demonstrate that there are trade-offs (i.e. increasing the benefits for one goal can result in disbenefits for another), particularly without coordinated efforts to support these strategies under a common vision (Spencer et

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al. 2017). According to a review on the interactions of mitigation and adaptation across multiple sectors, co-benefits often occur when climate action involves green infrastructure measures (Berry et al., 2015). In this context, green infrastructure (hereafter referred to as GI) has been identified as a promising option for such synergistic climate action (Yiannakou and Salata, 2017).

GI can be understood as a hybrid network of natural, semi-natural, and engineered features within, around and beyond urban areas at all scales, which is planned and managed to provide multiple ecosystem services and benefits (Tzoulas et al., 2007; Staddon et al., 2018). GI can include a wide variety of green and blue spaces, for example, forests, parks, allotments, and water bodies, and more engineered options, such as green roofs, vertical greenery, bioretention, and permeable pavements (Norton et al., 2015; Koc et al., 2017). The multiple functions of GI deliver ecosystem services (i.e. provisioning, regulating, and cultural services) and resulting benefits to humans that encompass environmental, social, and economic values (Hansen and Pauleit, 2014). These include, for example, reduced urban heat island (UHI) effects, increased CO_2 sequestration, improved water and air quality, improved social cohesion, more recreation and tourism opportunities, and increased property values, among many others (Naumann et al., 2011; Zölch et al., 2016).

Due to these multiple services and benefits, GI can be a strategic framework which integrates adaptation and mitigation objectives (i.e. climate benefits) with co-benefits for broader sustainable development (Locatelli et al., 2015; Yiannakou and Salata, 2017). For example, well-managed green roofs can simultaneously contribute to adaptation by reducing stormwater runoff and UHI effects as well as mitigation by increasing carbon sequestration and reducing building energy consumption, while providing aesthetic benefits and habitats for biodiversity (Oberndorfer et al., 2007; Shaw et al., 2007). In this sense, researchers have claimed that GI offers "no regrets" interventions and provides flexible, cost-effective and broadly applicable alternatives for climate action compared to conventional grey infrastructure (Byrne and Jinjun, 2009; Vignola et al., 2009; Jones et al., 2012).

The contribution of GI to climate adaptation has been widely addressed in the literature, for example, coping with UHI impacts by reducing air and surface temperature through shading and evapotranspiration of vegetation (e.g. Bowler et al., 2010; Zölch et al., 2016; Zardo et al., 2017), and managing flood risks by reducing stormwater runoff volumes and peak flows through interception, infiltration, retention and storage of rainwater (e.g. Lewellyn et al., 2016; Eckart et al., 2017; Maragno et al., 2018). Furthermore, there is an increasing number of studies on the role of GI in climate mitigation, for instance, by increasing carbon sequestration through photosynthetic absorption of vegetation and additional uptake from soils (Baró et al., 2014; De la Sota et al., 2019).

Despite the increasing discussions on adaptation, mitigation, and more broadly, multiple benefits of GI, there is little knowledge available addressing the linkages between the climate benefits and associated co-benefits as well as trade-offs (Sussams et al., 2015; Derkzen et al., 2017). Demuzere et al. (2014) presented a review on the contribution of GI to adaptation and mitigation in urban areas, but they covered a limited range of the interactions (i.e. co-benefits and trade-offs) and GI types. Recent studies have also made useful advances in the literature, but they often focus on individual climate benefits (e.g. Tiwary et al., 2014; De la Sota et al., 2019; Nordman et al., 2018; Alves et al., 2019); or mainly focus on health co-benefits (Harlan and Ruddell, 2011; Venkataramanan et al., 2019); or a particular case study context (Baró et al., 2014; Derkzen et al., 2015); or specific GI types (Russo et al., 2016; Salmond et al., 2016; Sharma et al., 2018), mostly with little emphasis on trade-offs. As cities turn increasingly to GI and other 'nature-based solutions' for climate adaptation and mitigation, a more comprehensive understanding of the climate benefits, co-benefits and trade-offs of GI is needed in order to maximize synergies and avoid unintended adverse impacts.

Against this background, this systematic literature review aims to synthesize the existing evidence on the contribution of GI to adaptation and mitigation, and the associated co-benefits and trade-offs, and to identify the types of GI that provide different climate benefits and co-benefits. This knowledge can be critical for informing the integration of climate actions into spatial planning and for the coordination of related policies and investments toward climate-resilient pathways for sustainable development. The co-benefits of climate action for health and the economy can be more immediate and visible than the climate benefits, providing a stronger rationale and motivation for its adoption and implementation (Smith, 2013; Deng et al., 2018). In order to facilitate GI research and practice that can deliver climate benefits and co-benefits while minimizing trade-offs, we need to know:

i. what are the benefits and co-benefits of green infrastructure associated with climate adaptation and mitigation?;
ii. what are the potential disservices and trade-offs associated with green infrastructure and how can they be managed?;
iii. what types of green infrastructure can deliver such climate benefits and co-benefits?

By answering the research questions, this study can provide researchers and practitioners with the typology, research trends, and knowledge gaps regarding climate (co-)benefits and trade-offs for different types of GI, as well as practical recommendations to optimize GI planning and design. Section 2 presents the methods for data collection and analysis, which is based on a systematic literature review and an analytical framework for assessing the climate benefits of GI in the literature. Section 3 illustrates the results of data synthesis on the overview of the studies, climate (co-)benefits, trade-offs, and studied GI types. In section 4, the results are discussed concerning linkages between benefits, and highlighting strategies that are necessary to maximize co-benefits and minimize trade-offs. Finally, in section 5, this study concludes with the key implications and potential directions for future research.

2. Methods

2.1. Search and selection of relevant studies

This paper applies a systematic literature review methodology according to the approach of Pickering and Byrne (2014) and the PRISMA statement (Moher et al., 2009) to collate relevant studies and synthesise their findings in a robust and transparent way. Systematic review can allow searching for a broader range of papers than the traditional narrative reviews and identifying, for example, geographical patterns, theoretical trends, and knowledge gaps in the literature (Rupprecht et al., 2015; Heymans et al., 2019).

The literature search was conducted using three databases: Web of Science, Scopus, and Google Scholar on the 6th March 2019 and updated on the 5th Oct 2019. These search engines were selected because they provide extensive coverage of the relevant journals (this was checked with a pilot search using Google Scholar) and they allow complex keyword strings for the literature search. In order to identify as many relevant studies as possible on GI explicitly providing climate benefits, the following phrase was used for the literature search: (“green infrastructure” OR “green urban infrastructure”) AND (“climate change” OR “climate action” OR “adaptation” OR “mitigation.”) As a result, 1,376 papers published from 1995 onwards were identified from the databases. Since only five papers were published up to 2007, no restriction on publication year was applied. After duplicates were removed, the abstracts were screened based on their relevance to the research questions. Articles were excluded if they were not written in English or the full texts were not accessible from the databases. For the remaining papers, the full texts were retrieved and assessed for eligibility. In order to be included in the review, studies were required to investigate climate adaptation or mitigation benefits as their thematic focus of the paper. In addition, they also must report an identifiable type of GI, and provide a clear link between the GI types and the climate benefits that they deliver. Thus, we did not include studies, for example, mainly focused on conceptual or methodological aspects of the climate benefits without explicit relations to GI types, or studies that only discussed general green spaces or green corridors without specific descriptions of the types of GI. Articles only marginally related to the topic of the review were also excluded. Through the screening process, a total of 141 papers were finally included in this review for data extraction and synthesis. The PRISMA flowchart illustrates the search process and results as shown in Figure 1.

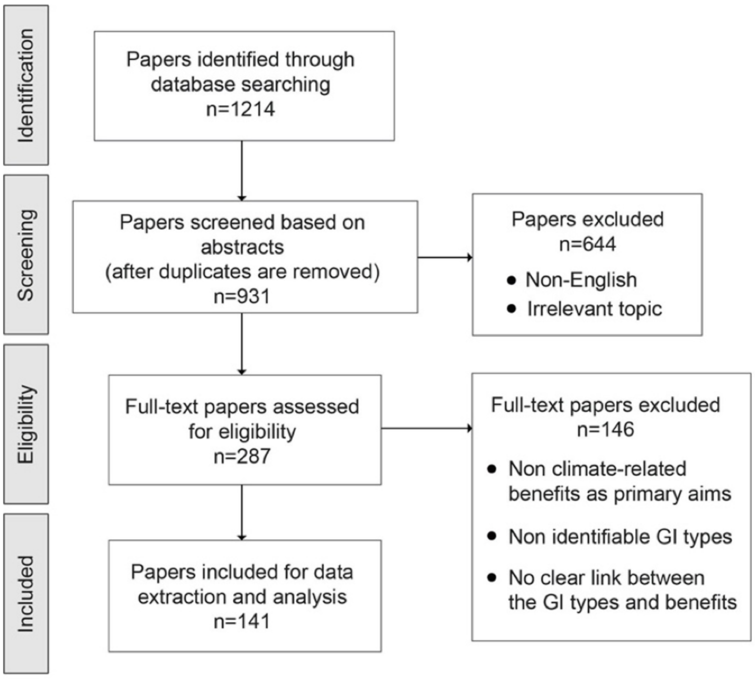

Fig. 1. Overview of reviewed papers identified in the steps of the systematic literature review inspired by the flow diagram from PRISMA (http://www.prisma-statement.org).

2.2. Data extraction and analysis

The 141 reviewed articles were analyzed in detail and the following information was recorded in a database:

- the publication year
- the location of the study;
- the climate change adaptation and mitigation benefits covered;
- the type of green infrastructure;
- any qualitative or quantitative information on co-benefits related to the climate benefits;
- any qualitative or quantitative information on trade-offs or disservices;

We structured the extraction of data, content analysis and synthesis of findings in terms of potential climate benefits, co-benefits, trade-offs, and the types of GI. The review was framed around the climate benefits, and the related co-benefits and GI types were investigated and interpreted. The GI benefits for adaptation and mitigation are categorized according to an analytical framework adapted from the European Environmental Agency (2011) and modified based on an initial review of all articles (Table 1).

Climate change adaptation	Climate change mitigation
• Heat stress reduction	• Carbon storage and sequestration
• Stormwater and flood management	• Energy use reduction
• Coastal flood protection	• Renewable energy opportunities
• Water scarcity management	• Sustainable travel promotion
• Ecosystem resilience improvement	

Table 1. Analytical framework for reviewing climate benefits of GI in the literature based on a preliminary review and EEA(2011).

Although previous reviews on the benefits of GI form the basis of this review (e.g. Young et al., 2014; Connop et al., 2016; Parker and Baro, 2019), categorization of multiple benefits of GI was challenging because of their complex interactions and different approaches applied in various disciplines. For example, almost all benefits reviewed can directly or indirectly be related to human health, including psychological and social benefits or economic wellbeing (e.g. Demuzere et al., 2014). Thus, we only counted the direct benefits of specific types of GI (e.g. mental or physical health benefits of trees), and we discuss indirect benefits (e.g. their monetary values or avoided social costs) in a later section.

During the preliminary review, we found that the GI concept and classification of GI types can be variable due to different interpretations of GI depending on countries, research contexts, and the main purpose of a study. In particular, selective application of sustainability objectives in different GI development contexts leads to different definitions and interpretations depending on whether GI must use ecological resources (Wright, 2011) or whether it includes natural green space or only highly modified landscapes for public benefit (Byrne et al., 2015). However, it is difficult to separate out green and grey infrastructure precisely (e.g. cycle paths through green areas confer added benefit for recreation), and researchers often consider non-ecological resources as GI (e.g. permeable pavements and rainwater barrels). Thus, this study employed a green-grey continuum covering natural green, engineered green, and functional green (‘sustainable’ but not including ecological resources), to flexibly accommodate the GI features identified during the review (Figure 2). Each type of GI measure was categorized using the author’s description if provided.

Due to the diversity of the contexts, GI types and indicators reported in the literature, the extracted information on the links between different thematic aspects was analyzed by using a vote-counting approach and descriptive statistics according to the frequency of citations related to each thematic factor (Smith et al., 2017). Thus, the counted number of citations presented in the results section reflects only the number of papers citing the existence of evidence in the reviewed studies, and not necessarily the significance or strength of the link. Similarly, the absence of numbers does not indicate that no link exists, but there is no or weak evidence identified in the extracted literature. For the location of the study, the countries and continents of studied case areas, if provided, were used to identify the geographical patterns. During the data extraction process, other information was also documented including the spatial scale of the study, methodological approaches, and important attributes for the effective provision of each benefit presented in the paper. Although some of them are briefly elaborated in the discussion section for a better understanding of the results, the main theme of this paper focuses on the climate (co-)benefits, trade-offs, the types of GI, and their linkages.

Fig. 2. The green-grey continuum and its illustrative examples (source: own elaboration based on Wrights, 2011; Mell, 2013; Grimm et al., 2016; Depietry and McPhearson, 2017; Davies et al., 2006).

3. Results

3.1. Research trends

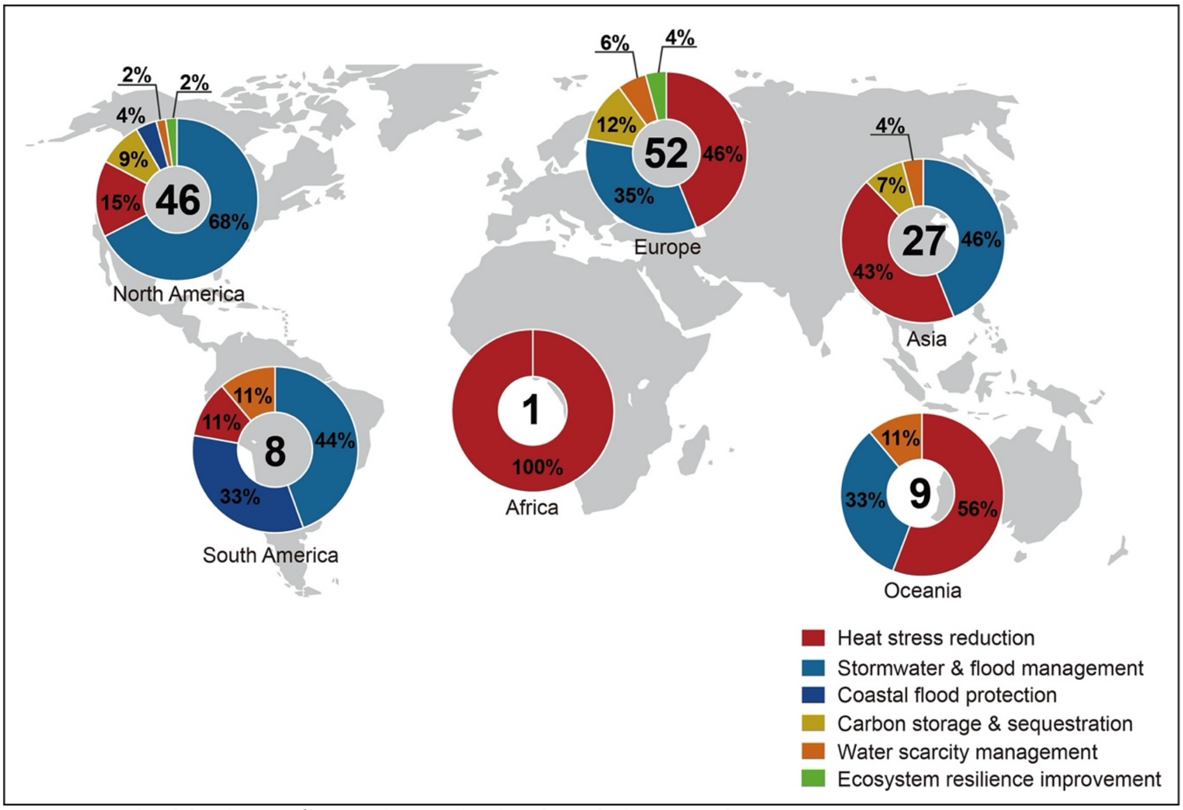

Fig. 3. Geographical distribution of reviewed papers based on the studied case areas by continents.

The geographic distribution of study sites illustrates that papers are predominantly focused on Europe (37%), North America (33%), and Asia (20%) (Figure 3). Far fewer locations were studied in Oceania (6%), South America (6%), and Africa (1%) approximately. This shows the increasing interest in studies of the climate benefits provided by GI in relatively developed and industrialized countries, while these aspects have not received the same attention in most developing countries. In a country-based analysis, a heavy geographic bias was observed as papers studied sites in the USA (24%), UK and China (7% each): the Netherlands, Australia, Italy and Germany (5% each) and South Korea (4%).

Notably, different research interests were observed between the continents, most of which were relatively focused on certain climate benefits, for instance, North America on flood management, and Oceania and Africa on heat stress reduction. Such geographically divergent research scopes could be attributed to different research interests based on their climatological characteristics. For example, research into heat stress reduction is less likely in some high latitude countries where the solar intensity is low (Koc et al. 2018). While research scopes varied across continents, Europe and North America have more diverse research topics than others. Accordingly, studies on ecosystem resilience improvement, for example, were found only in Europe and North America.

Although the concept of GI emerged in the 1990s (Mell, 2017), its role in addressing climate change was explicitly studied from 2007 in the scientific literature (Gill et al., 2007) as identified in this review (see Fig. S1). Only since 2014 has the rate of annual publications begun to increase. The majority of papers (80%) were published in the last four years, illustrating that the contribution of GI to addressing climate change is a rapidly growing field of research (Mell, 2017). The recent increase in the number of publications has been particularly driven by articles on flood management with study sites in the USA published from 2017 (16%).

3.2 Climate benefits

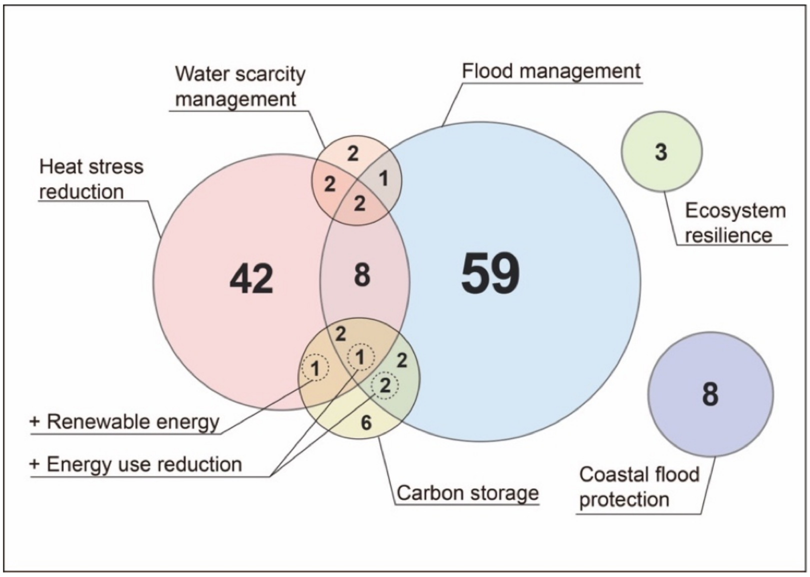

Fig. 4. The number of papers that studied different climate benefits provided based on primary aims of the reviewed articles. Note: sizes are not proportional to the number of studies and the dotted circles illustrate other mitigation benefits studied in addition to each overlapped climate benefits.

Analysis based on the primary aims of the 141 papers shows that research on climate benefits provided by GI was strongly focused on adaptation benefits (90%): most studied flood management (55%) and heat stress reduction (41%) individually, or jointly (Figure 4). Articles examining coastal protection (6%), water scarcity management (5%), and ecosystem resilience improvement (2%) were less numerous. In comparison to adaptation benefits, far fewer articles investigated mitigation benefits (10%), The articles were predominantly on carbon storage and sequestration, while other mitigation benefits regarding energy use reduction and renewable energy opportunities were studied only in combination with carbon storage and sequestration or other adaptation benefits such as flood management and heat stress reduction. None of the reviewed articles focused solely on such mitigation benefits. Articles promoting sustainable travel (e.g. green cycle paths and foot paths) were not identified. Although researchers studied renewable energy opportunities and energy use reduction in buildings or water treatment plants, they often examined economic values (e.g. cost reduction for heating or water treatment) and overlooked or implicitly stated the mitigation benefits from carbon emissions avoided due to reduced use of fossil fuels. Despite the potential contribution of GI to adaptation and mitigation simultaneously, a limited number of articles (10%) studied both benefits in an integrated way.

Out of 141 articles reviewed, 21 (15%) examined two or more climate benefits as their primary focus, of which flood management and heat stress reduction were the most frequently studied benefits. While water scarcity management and carbon storage and sequestration were mainly investigated with other climate benefits rather than as the primary focus, coastal protection and ecosystem resilience improvement were only investigated individually, although the GI literature on these two remains sparse. When more than three climate benefits were jointly studied, articles typically examined carbon storage and sequestration together with flood management and/or heat stress reduction.

3.3 Links between climate benefits and co-benefits

Climate benefits	Flood management	Heat stress reduction	Water scarcity management	Coastal flood protection	Ecosystem resilience improvement	Carbon storage and sequestration	Energy use reduction	Renewable energy opportunities	Water quality improvement	Groundwater recharge	Erosion control	Air quality improvement	Health/wellbeing	Environmental education	Noise reduction	Aesthetic/amenity	Recreation/tourism	Environmental justice	Real estate value	Food production	Building management cost reduction	Green job opportunities
	Environmental											Social								Economic		
Stormwater and flood management		10	6		5	4	9	2	17	4		10	3	3	3	4	4	1	2	2	4	
Heat stress reduction	8		1		2	2	7	1	1			8	3		5	4	6	2	1	1	1	
Water scarcity management	4	4			1	1		1	3	1		1	1								1	1
Coastal flood protection			1		6				1	1	7			1			3					1
Ecosystem resilience improvement																						
Carbon storage and sequestration	7	7	1		1		4	1	3	1		8		1	3	1	1		1		1	

Table 2. the number of studies showing a link (not including unclear) between climate benefits and co-benefits. More frequently cited links are highlighted in darker shades of orange.

Table 2 shows the multiple co-benefits of GI associated with each climate benefit. Rather than a fixed classification, the identified co-benefits are loosely listed along the continuum of environmental, social, and economic benefits representing the three sustainability dimensions. It can be challenging, and even misleading, to organize the multiple benefits into fixed categories because almost all benefits can have direct or indirect implications for environmental, social, or economic values simultaneously. For example, although many studies classified temperature reduction and air quality improvement as environmental benefits (e.g. Alves et al., 2018), they also carry significant social values given their potential contribution to physical and mental health/wellbeing benefits through decreased heat stress and improved respiratory health.

Analysis reveals that a wide variety of co-benefits is associated with each climate benefit. Flood management has the most types of co-benefits, of which water quality improvement was the most commonly studied, followed by temperature reduction, air quality improvement, energy savings, water saving/supply and ecosystem resilience. Heat stress reduction also has a considerable number of co-benefits; most commonly flood management, air quality improvement and energy savings, followed by recreation/tourism and noise reduction.

Fewer co-benefits were studied for the other climate benefits. Studies on water scarcity management focused mainly on flood management and heat stress reduction co-benefits, while for coastal flood protection the main co-benefits were erosion control and ecosystem resilience improvement. Although co-benefits of ecosystem resilience improvement were not found in this review, there is evidence that GI practices that increase habitat area and improve biodiversity can have a positive influence on other ecosystem services (Smith et al., 2017). For climate mitigation benefits of GI, carbon storage was frequently studied with air quality improvement as win-win solutions or co-management (Baró et al., 2014; Tiwary et al., 2014). There was no article solely focused on energy savings and renewable energy opportunities since they were mainly identified as co-benefits in the literature rather than the primary reason for implementing a scheme, so in Table 2 they appear only as co-benefits instead of climate-benefits. Energy saving was, however, a commonly cited co-benefit from most of the other climate benefits whereas papers discussing renewable energy opportunities were rarely found.

When sorted by individual co-benefits, a strong bias was observed towards environmental values. For instance, the most prevalent benefits included water and air quality improvement, heat stress reduction, flood management, energy savings and carbon storage, most of which were intended to enhance environmental condition (Kim and Song, 2019). In contrast, GI benefits closely related to socio-cultural and economic values did not receive the same attention from researchers even though these were frequently discussed as potential co-benefits to be addressed in future studies. These included aesthetic/amenity, environmental education and justice, and health/wellbeing benefits (socio-cultural), as well as increased property values and reduced building management costs (economic values). This indicates that socio-cultural and economic benefits of GI are often well acknowledged, but articles studying these benefits with regards to climate change are not common.

3.4 Links between GI features, climate benefits and co-benefits

Climate (co-)benefits	Natural green (ecological resources) →											Engineered green							Functionally green(grey)					
	individual tree	Forests/clustered tree	Shrub/hedge	Grass/herb	Soil/bare ground	Sand dune	Park	Garden	Water body	Riparian vegetation	Beach	(Urban)agricultural land	(Artificial)reef	(Constructed)wetland	Bioswale	Bioretention/rain garden	Retention pond	Detention pond	Green roof	Green wall/facade	(Green)brownfield	Infiltration trench	Permeable pavement	Rainwater harvesting/barrel
Flood management	18	13	9	13	3		3	5	8	1		6		10	26	38	7	9	41	2		12	31	22
Heat stress reduction	39	17	11	18	3		11	5	12	1		3		2	4	5	1		26	13	2	1	5	
Water scarcity management			1	1			1	1	2					4	1		2	1	3			1		8
Coastal flood protection		2				3					2		6	6										
Ecosystem resilience improvement	2	4	3	3		1			1		1		4	4	1	2	1		5	1	1			
Carbon storage and sequestration	9	7	4	2			2	2		1		1			1	2			7					
Energy use reduction	7	1					1					1				1			12	1				
Renewable energy opportunities	1	1	1																2					
Water quality improvement	4	1				1		1				1		8	14	19	5	4	15			4	12	
Groundwater recharge	1	1	1	1			1	1		1		1		1	2	5						2	4	
Erosion control		2				2					1		4	3										
Air quality improvement	13	7	4	4			2	3		1		1			1	3			11	2			1	
Health/wellbeing	2		1	1								1							2					
Environmental education	1					1								1	1	2								3
Noise reduction	3	1	3	1			1	1											2	2			1	
Aesthetic/ amenity	3	2		1			1	1							1	2	1	1	4	1				
Recreation/tourism	3	1	1	2		1	1	1	1		1		2	3	1		1	1	3		1			
Environmental justice	1						1									1			3	1	1			1
Real estate value	1	2								1				1	1	1	1		1	1			1	
Food production																			1					
Building management cost reduction																			6	1				
Green job opportunities						1							1	1					1					

Table 3. the number of studies showing a link (not including unclear) between climate benefits and GI types. More frequently cited links are highlighted in darker shades of orange.

Table 3 shows the result of the descriptive analysis of GI types based on the 141 studies reviewed. The individual types of GI are roughly classified based on a green-grey continuum along natural green (ecological resources), engineered green (engineered-ecological structures), and functional green (grey infrastructure with sustainable objectives) to accommodate all identified GI features in the literature with a flexible categorization (Davies et al., 2006; Wright, 2011; Mell, 2013).

The analysis revealed the links between the GI features and the climate benefits they deliver, based on the level of evidence in the literature. It is not possible to determine the most effective features for particular benefits, as analysis of their performances varied significantly owing to different site conditions. Among the climate benefits, flood management employed the widest range of GI measures, focused on green roofs, bioretention/rain gardens, and permeable pavements but also using bioswales, rainwater harvesting/barrels, and individual trees. This wide range is partly because many researchers, particularly for sites in the USA, consider GI and Low impact development (LID) as the same approach and use LID scheme elements such as rainwater barrels within GI practice. Articles on UHI and heat stress reduction also studied a wide range of GI features including individual and clustered trees (i.e. forests), green roofs, grassland, green walls/facades, water bodies and parks.

In contrast, other climate benefits tended to focus on limited types of GI. For example, almost all papers looking at carbon storage and sequestration investigated the direct mitigation benefits through potential carbon uptake of trees and forests. The indirect mitigation benefit from energy saving was mainly provided by individual trees near buildings or green roofs/facades, largely through reduced building energy demands for heating and cooling and avoided carbon emissions, while some studies also examined energy use reduction in water treatment plants resulted from reduced stormwater volume and improved water quality. A few papers discussed renewable energy opportunities of GI using biomass energy production from trees, forests, and shrubs. GI features with rainwater retention and storage functions (rainwater harvesting/barrels, green roofs, wetlands, and water bodies) were closely related to water scarcity management. Articles examining coastal flood protection utilized different GI practices suited to coastal areas, i.e. coastal wetlands, oyster and coral reef structures, beaches, dunes and coastal forests. Ecosystem resilience improvement employed diverse features across multiple scales such as green roofs, bioretention, wetlands, trees and forests, to provide habitats in cities.

In addition to climate benefits, there was relatively strong evidence for delivery of some types of co-benefits by particular GI features. For instance, water quality improvement and groundwater recharge are both provided by GI features that enhance rainwater infiltration, such as bioretention areas, permeable pavements, and bioswales. Studies of air quality improvement focused on trees, shrubs, forests, and green roofs. Less commonly studied links included reduced building management costs through the increased lifespan of green roofs; reduced traffic noise from trees and shrubs; and increased aesthetics and property values from GI features near houses (trees, bioretention, and green roofs).

An analysis based on individual GI types illustrates that some schemes were particularly multifunctional and have attracted more attention from researchers, including green roofs and walls, trees and forests, bioretention, wetlands and bioswales. In contrast, a limited range of benefits were studied for water bodies (heat stress reduction and flood management) and green walls/facades (heat stress reduction) although they could have more benefits than were identified in this review.

3.5. Trade-offs

Of the 141 papers reviewed, 41(28%) discussed trade-offs between benefits and disservices of GI, which can be categorized into four aspects (Table 4): (1) UHI and heat stress; (2) air quality and carbon emissions; (3) water-related problems (water quality, scarcity and groundwater recharge); and (4) health/wellbeing and economic disadvantages. The most prevalent problems examined were associated with heat stress reduction, mainly related to decreased solar access caused by the tree canopy and its shading. Some examples of this included seasonal temperature reduction in winter leading to increased heating demands; reduced ventilation causing increased local temperature and thermal discomfort, for example, when trees are densely combined with shrubs/grasses (heat-trapping effects); and decreased renewable energy potential of rooftop solar panels. Green and blue spaces intended to offer cooling benefits might also have a higher temperature than surrounding urban areas owing to diurnal temperature changes (nocturnal warming effects) particularly without tree shading above them.

Also, researchers studied trade-offs regarding air quality, which were mostly caused by trees. The most common problems were health impacts from emissions of volatile organic compounds (VOCs) and pollen from trees, and increased air pollution due to poor ventilation or resuspended air pollutants from street trees. Several studies also investigated carbon emissions through tree management activities using fossil-fuel based machinery as well as trade-offs between renewable energy provision (biomass combustion) and air pollution.

Regarding water-related problems of GI, some papers examined water quality problems, many of which resulted from green roof fertilization. When looking at water scarcity, trade-offs between irrigation and cooling/carbon storage benefits of green spaces were frequently studied, which puts more pressure on limited urban water resources during drought periods in (semi-)arid climates. Only a few articles explored trade-offs regarding groundwater recharge between retention/detention and infiltration functions of GI for stormwater management.

Some studies discussed GI disservices affecting overall human health and social/economic wellbeing, including obscured views, fears of crime, disease, insects and other animals (e.g. nesting birds). Of the various costs involved, those related to vegetation root-induced damage to infrastructure and increased resource requirements for maintenance (e.g. energy and labor) were the most commonly studied.

Heat stress reduction

Nocturnal warming: due to diurnal temperature variations of vegetation, green areas (e.g. parks) could increase temperatures during the night, which can decrease human thermal comfort and increase heating energy demands (potential trade-offs: cooling & energy savings/wellbeing). (2)(12)(14)

Tree shades in winter: trees could prevent solar radiation penetration and decrease temperatures during the winter, which lead to negative health impacts, decreased human thermal comfort, and increased heating energy demands (potential trade-offs: cooling & energy savings/health). (1)(2)(6)(9)

Tree shades and renewable energy opportunities: shading from tree canopies near buildings could reduce solar radiation access, thus reducing renewable energy assimilation from rooftop photovoltaic systems (potential trade-offs: cooling/energy savings & renewable energy opportunities). (7)(10)

Heat-trapping: densely planted trees with shrubs/grasses could reduce ventilation and prevent heat dissipation, causing increased local scale temperature and decreased human thermal comfort (potential trade-offs: carbon storage & cooling). (9)(13)(14)

Permeable pavements: can have higher surface temperatures than impermeable pavements during hot summer days depending on the specific conditions (e.g. materials and porosity), which might cause an adverse impact on human thermal comfort (potential trade-offs: flood management & cooling/wellbeing). (17)

Air quality and carbon emissions

bVOCs emission: emitted bVOCs from street trees may increase ozone concentrations at the presence of NO_x from traffics, and thereby cause air pollutions and associated health problems (potential trade-offs: cooling/carbon storage & air quality/health). (2)(3)(4)(5)(15)(19)(31)(35)(37)(38)

Tree pollen and health impacts: exposure to allergenic pollen from trees is associated with a range of health effects, including allergic rhinitis, asthma, and eczema (potential trade-offs: cooling/carbon storage & air quality/health). (2)(3)(4)(19)(35)

Street trees and air quality: densely planted trees and shrubs on both sides of streets might reduce mixing and dispersion of wind flow, thus preventing ventilation and increasing air pollutant concentrations (potential trade-offs: cooling/noise reduction & air quality). (2)(4)(5)(18)(19)(38)(39)

Resuspension from tree canopies: trees might re-suspend air pollutants into the air than they deposited if there are a strong wind and no rain, particularly in dry and semi-arid regions (potential trade-offs: cooling & air quality). (2)(33)

Implementation and maintenance activities: urban trees require regular maintenance efforts involving fossil fuel-based machinery activities (e.g. pruning and transport), which might emit carbon back into the atmosphere in the short-term (potential trade-offs: cooling/aesthetic & carbon storage/air quality). (31)(32)(35)(39)

Biomass-based renewable energy: during the generation process of Combined Heat and Power systems, biofuel and heat provision can increase GHG gas (e.g. NO_x, N_2O) and SO_2 and HCl emissions detrimental to air quality, exacerbating health risks (potential trade-offs: renewable energy opportunities & air quality/health). (30)

Invasiveness: tree and hedge species with high potentials for air quality improvement can be highly invasive in other regions (potential trade-offs: air quality & biodiversity). (19)(31)

Water quality

Green roof fertilization: intensive green roofs which require frequent fertilization can expose runoff to more nutrients (e.g. phosphorus, nitrogen, mercury), and thereby reduce the stormwater quality (potential trade-offs: flood management & water quality). (20)(36)(37)

Infiltration-based GI practice and water quality: permeable pavements and bioretention might have high levels of nutrients and pollutants in runoff (e.g. pesticides, pathogens, heavy metals, salts) and cause water quality degradation and groundwater contamination (potential trade-offs: flood management & water quality). (17)(23)

Water scarcity and groundwater recharge

Irrigation of GI: vegetation that requires frequent irrigation can exacerbate water scarcity particularly during drought periods in arid climates (potential trade-offs: cooling/carbon storage & water scarcity management). (8)(16)(28)(29)(35)(37)

Shallow water bodies and irrigation: swales, ponds, and water gardens might require frequent water inputs to retain water column, causing negative impacts on the long-term water sustainability (potential trade-offs: cooling & water scarcity management). (11)(29)

Stormwater GI and water quality: GI practice implemented in water scarce regions could reduce rainwater volume to receiving water bodies, having adverse impacts on the water supply of the region (potential trade-offs: flood management & water scarcity management). (26)

Stormwater GI and groundwater recharge: effective daytime evaporative cooling from stormwater GI practice (e.g. rain gardens and bioretention) could lead to reduced groundwater recharge (potential trade-offs: cooling & groundwater recharge). (20)

Health/wellbeing and economic disadvantages

Nuisance species: stormwater GI practice in particular such as rain barrels, retention ponds, and water bodies may provide habitats for nuisance species (e.g. mosquitos) and pose a health problem as carriers of diseases (e.g. Lyme disease) (potential trade-offs: flood management/cooling & health/wellbeing). (2)(11)(22)(24)

Damage to infrastructure: trees and green roofs may pose damage to the built environment due to vigorous root growth, bVOC emissions and resulting ozone concentrations, or fallen limbs, creating safety issues (potential trade-offs: cooling/flood manage mental health/wellbeing). (2)(7)(10)(15)(16)(25)(31)(35)(38)

Vegetation around houses and roads: could block views or prevent access or exit, which can be associated with increased fear of crime, difficulties in the navigation, or reduced visibility (potential trade-offs: cooling/aesthetic & health/wellbeing). (2)(3)(10)(35)

Social costs to the community: vegetation can also cause economic burden to the community, for example, increased potential for bushfires in hot and dry conditions as well as additional resources of energy and labor for maintenance activities (potential trade-offs: cooling/carbon storage & health/wellbeing). (2)(3)(10)(19)(21)(25)(37)

Table 4. Trade-offs and disservices of GI with exemplary potential trade-offs between benefits. Adapted from: (1) Coronel et al. (2015) (2) Salmond et al. (2016) (3) Russo et al. (2016) (4) Buccolieri et al. (2019) (5) Simon et al. (2019) (6) Park et al. (2020) (7) Staley (2015) (8) MacIvor et al. (2016) (9) Saaroni et al. (2018) (10) Lin et al. (2016) (11) Gunawardena et al. (2017) (12) Zölch et al. (2019) (13) Imran et al. (2019) (14) Fung and Jim (2019) (15) Tiwary and Kumar (2014) (16) Gill et al. (2007) (17) Xie et al. (2019) (18) Pochee and Johnston (2017) (19) Blanusa et al. (2019) (20) Prudencio and Null (2018) (21) De Sousa et al. (2012) (22) BenDor et al. (2018) (23) Eckart et al. (2017) (24) Chen et al. (2019) (25) Brudermann and Sangkakool (2017) (26) York et al. (2015) (27) Reyes-Paecke et al. (2019) (28) Yang and Wang (2017) (29) Wong et al. (2017) (30) Tiwary et al. (2014) (31) Baró et al. (2014) (32) De la Sota et al. (2019) (33) Amini Parsa et al. (2019) (34) Neto and Sarmento (2019) (35) Parsa et al. (2019) (36) Sarkar et al. (2018) (37) Pataki et al. (2011) (38) Tiwary et al. (2016) (39) Derkzen et al. (2015).

3.6. Bundles of climate co-benefits, trade-offs, and GI features

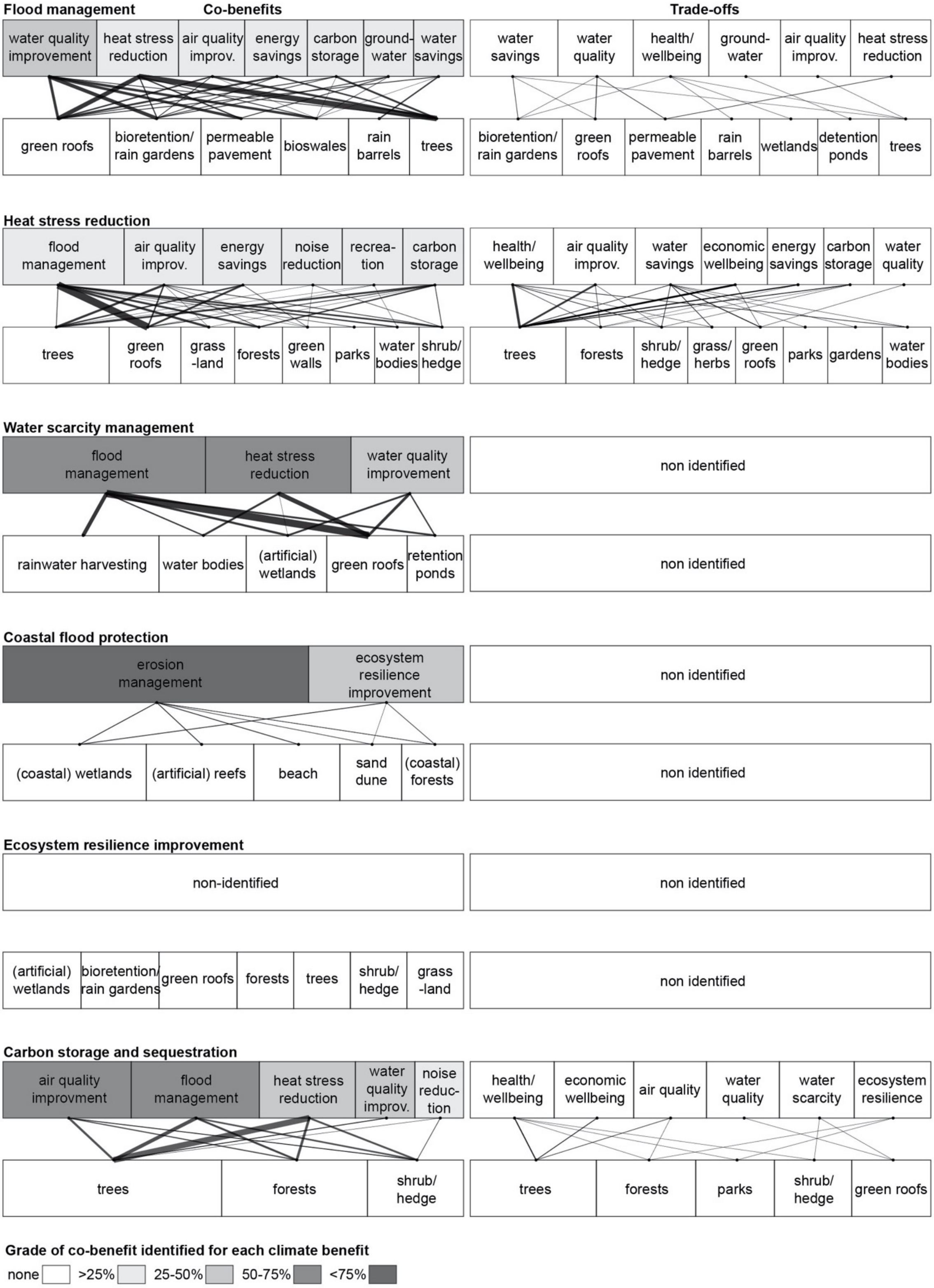

Figure 6. Summary of typology showing the link between the bundles of major GI types and their co-benefits (left column) and trade-offs (right column) based on each climate benefit as identified in the table 2. Note: line thickness is proportional to the number of studies supporting each link.

Fig. 5. Summary of typology showing the link between the bundles of major GI types and their co-benefits (left column) and trade-offs (right column) based on each climate benefit as identified in the table 2. Note: link thickness is proportional to the number of studies supporting each link.

Based on the analyses in the previous results, we identified some patterns in GI types and climate co-benefits. This led to the development of a simple typology for classifying bundles of major GI features and co-benefits and trade-offs commonly associated with each climate benefit (Figure 5). Bundles were identified where there were a large number of studies regarding (i) the relevance of climate benefits and (ii) the multitude of co-benefits to maximize multifunctionality, and (iii) clear links between those major types and benefits. In this section, we present an overview of the bundles identified for each climate benefit, which can be used to improve delivery of each climate benefit and associated co-benefits while acknowledging relevant trade-offs and suggesting exemplary solutions. It should be noted that the patterns were based upon the number of reviewed studies, and thus do not necessarily suggest that specific GI features and benefits are more significant or effective than the others.

3.6.1 Flood management

For flood management, a bundle of six GI types with multiple benefits was identified that can provide a bundle of eight co-benefits, if well planned and managed. The major GI features were mainly associated with stormwater infiltration, retention/detention, and storage. GI concerning stormwater and flood management is also framed as green stormwater infrastructure and researchers often used the terms LID or 'best management practice' interchangeably. Most papers tended to analyze the individual or combined effects of multiple GI types (e.g. bioretention, green roofs, and permeable pavements) in reducing total runoff volumes and peak flows at city or regional watershed scales (macro-scales), or small catchments at district scales (meso scales). At building or site scales (micro scales), articles investigated such benefits through one or two types of GI practices (e.g. trees and green roofs). Although it is difficult to determine the performance of GI schemes in flood management, several reviews noted that they can be significantly effective at controlling the hydrological impacts of storm events with low-intensity, duration, and antecedent moisture levels in a warm season. For large storm events, the capacity of GI strategies diminishes with increasing storm intensity and performed best when combined with grey infrastructure for rainwater detention and storage (Eckart et al., 2017; Sohn et al., 2019). About one-third of the literature studied included improving runoff water quality, which can be delivered by almost all green stormwater infrastructure, mainly focused on reducing pollutant loads like suspended solids, nitrogen, and phosphorus. Moreover, the stormwater GI schemes can also provide groundwater recharge and water saving benefits (through infiltration and retention/storage functions), however, possible trade-offs regarding the two water-related co-benefits should be acknowledged and tackled during implementation and management (see section 3.5), for example, by arranging green roof fertilization according to the species' nutrient requirement and seasonal conditions (e.g. rainy season).

3.6.2 Heat stress reduction

GI features offer cooling benefits through several ecosystem functions such as evapotranspiration, shading, and low solar absorption capacity (Zardo et al., 2017). Notably, the evidence on cooling benefits of typical green spaces like parks or forests was lower than for some common GI features (e.g. green roofs) because researchers analyzed the components of green spaces individually (trees, grass, and shrubs), instead of as a whole (park).

The majority of the studies investigated the cooling effects of GI measures on air temperature and human thermal comfort at site scales (e.g. buildings and street canyons) or the magnitude and intensity of its effects on air and surface temperature at meso scales (e.g. neighborhoods and districts). At macro scales (cities or regions), articles mainly explored the widespread role of green spaces and water bodies in reducing surface temperature and UHI. A review of the cooling impacts of GI by Bowler et al. (2010) suggested that an urban park can reduce temperatures in surrounding areas up to 1°C.

Research on the effectiveness of temperature reduction tends to focus on identifying cooling intensity and distance of green spaces, which depend on several attributes: size, shape, canopy coverage, tree species, characteristics of surrounding areas, weather patterns (Gunawardena et al., 2017; Zardo et al., 2017). For example, the cooling intensity of green spaces can be higher with a larger size, regular and circular shapes, wider canopy coverage, while cooling distance tends to increase with a larger size, irregular and elongated shapes, and lower wind velocity. Therefore, in order to maximize cooling benefits of GI, it is important to determine optimal balancing between size, shape, and tree canopy coverage and careful selection of species according to site conditions (Feyisa et al., 2014). Also, networks of wooded green spaces with adequate size (e.g. 2ha) can be more effective than open, grassed green spaces although utilizing diverse types of GI can be critical (Doick et al., 2014).

However, in implementing GI practice for temperature reduction purposes, appropriate measures are crucial to tackle relevant trade-offs and avoid adverse effects. Some examples of such measures can be selecting deciduous trees species with fewer leaves during winter to minimize the negative impacts of seasonal temperature reduction especially in high latitude cities (Saaroni et al., 2018). In designing and managing green spaces to maximize cooling benefits while avoiding adverse heat-trapping effects and thermal discomfort, decision-makers need to identify main wind channels and keep this area open from trees but planted with grass, for sufficient ventilation and reduced heat storage (Zölch et al., 2019).

3.6.3 Water scarcity management

For GI contribution to water scarcity management, the climate benefits heavily depend on the GI types that can store and reuse rainwater such as rain barrels, water bodies, and retention ponds. Rain barrels are effective and easily maintainable retention and detention devices that are applicable to urban areas (Abi Aad et al. 2010; Damodaram et al. 2010). Harvesting rainwater with appropriate tank sizes can be used to control stormwater runoff and meet 50% of non-potable water demand for human uses such as toilet flushing, garden irrigation, and washing machines (Roebuck 2007; Zahmatkesh et al., 2015). However, it is essential to employ more diverse GI practices than rain barrels to promote co-benefits because they have few co-benefits.

In GI practice for water scarcity management, trade-offs regarding GI irrigation and temperature reduction are particularly important given the increasing impacts of climate change on heat stress and droughts especially in (semi-)arid climates. However, water consumption can be optimized since current water use for irrigation might be higher than actual demands owing to over-irrigation, for example, in gardens and extensive lawn surfaces as argued by Reyes-Paecke et al. (2019). This might offer a chance to save water and cope with water scarcity in the future. Another potential solution to minimize the trade-offs can be the adoption of xeriscaping in semi-arid climates, which can considerably reduce water demand for irrigation, due to the water-buffering capacity of xeriscaping, but at a cost of an increase in ambient temperature (Yang and Wang, 2017). It is also recommended to schedule the irrigation practice according to the species' water requirements and growth stage as well as to introduce trees with low water requirements in arid and semi-arid regions (Amini Parsa et al., 2019).

3.6.4 Carbon storage and sequestration

The literature on carbon storage and sequestration typically investigated the direct mitigation benefit of potential carbon uptake in biomass using individual and clustered trees (i.e. urban forests), frequently reported with co-benefits of air quality improvement, flood management and heat stress reduction. Generally, the amount of carbon stored was highly dependent on the tree species, diameter at breast height (dbh), tree height, and tree condition (Neto and Sarmento, 2019; Parsa et al., 2019). Urban forests have much less capacity for carbon storage (e.g. 50%) compared to natural forests because of the young age of trees, as the planted trees need more than 20 years to deliver all their benefits (Amini Parsa et al., 2019). Thus, the implementation of GI strategies would have a non-negligible but limited effect on carbon mitigation and air quality levels at the city level (Tiwary et al., 2016). In this sense, the use of urban forests for climate mitigation and air quality improvement would play a complementary role to other strategies rather than an alternative measure (Baró et al., 2014). Nevertheless, decision-makers should consider GI-based strategies because they present a feasible option in cities with limited urban resources to offset carbon emissions and would be more cost-effective if the provision of other co-benefits were considered such as temperature reduction and health/wellbeing (Amini Parsa et al., 2019). Further, for effective delivery of benefits, GI-based efforts to abate GHG emissions in cities should be coordinated with other sustainable goals at larger scales (e.g. regional scales) (Baró et al., 2014).

A further critical issue is trade-offs with other benefits or possible disservices. Unlike natural forests, urban trees require significant maintenance efforts involving fossil-fuel based machinery activities (e.g. removing and transferring deadwood, leaves, and pruned branches). Hence, it is essential to minimize the use of oil-based machinery and promote renewable sources of energy as well as consider net carbon balance incorporating both CO_2 uptake and emissions in GI plans and managements (De la Sota et al., 2019).

Other disservices of trees implemented for carbon storage can also be overcome so as to limit negative outcomes and maximize positive benefits through applicable solutions, including: (i) appropriate choice of species and management according to the ecological and climatological condition in site areas (e.g. bVOC and pollen emissions); (ii) placement of trees along roads, not well-used by pedestrians (e.g. trees at street canyons decreasing air quality due to reduced air mixing) (iii) securing sufficient spacing of trees from infrastructure (e.g. tree roots damaging buildings and pavements) (Gill et al., 2007; Pochee and Johnston, 2017).

3.6.5 Coastal flood protection

For coastal flood protection, studies tend to focus on the potential of GI schemes to protect coasts from flooding by attenuating wave energy and from erosion by reducing wave transmission and capturing sediments (Conger and Chang, 2019). Some types of coastal vegetation such as coastal forests, wetlands, and dunes can also contribute to ecosystem resilience improvement by providing wildlife habitats. It is also framed as coastal green infrastructure (CGI) and researchers often used other related terms (e.g. nature-based infrastructure and nature-based solutions) (Conger and Chang, 2019; Schoonees et al., 2019). Although attributes that determine the magnitude of wave attenuation are variable among different CGI practices, coastal wetlands are influenced by width, height, and canopy density (Saleh and Weinstein, 2016). The effectiveness of CGI in blocking storm surges is highly context-dependent, but some researchers commented that tidal marshes and wetlands can reduce wave energy from low-to-moderate-energy storms while their capacity to reduce high-energy storm surges remains limited and poorly quantified (Saleh and Weinstein, 2016; Gedan et al., 2011) and are most effective if combined with engineering features as hybrid solutions comprising green and grey infrastructure (Saleh and Weinstein, 2016). In this sense, ecologically enhanced grey infrastructure or hard solutions (e.g. sea walls and dikes) can also be regarded as green infrastructure under the label of hybrid or engineered green infrastructure if adaptations are made to allow organisms to settle (e.g. vegetated revetments and green dikes), and thereby offering ecosystem services and benefits (Schoonees et al., 2019).

3.6.6 Ecosystem resilience improvement

There is a bundle of several GI types that can contribute to ecosystem resilience improvement by supplying new or improved habitats or strengthening ecological networks to reduce habitat fragmentation. The evidence on co-benefits was rarely explored because most literature reviewed focused solely on biodiversity conservation opportunities for climate adaptation of specific target species in and around cities although GI does not automatically deliver biodiversity conservation benefit without its explicit consideration. However, more research is still required on how biodiversity can fit into or be affected by GI-based climate action (Butt et al., 2018). Therefore, it is important to ensure that GI practices are undertaken in a synergistic way with ecosystem resilience improvement while acknowledging possible trade-offs as species with high potentials in some climate benefits (e.g. carbon storage and air purification) could be invasive in other climate regions. Using diverse and native species where possible and planting larger trees may lead to improved biodiversity benefits and better ecosystem resilience.

4.Discussion

4.1. Research overview and gaps

Although existing research has made significant progress regarding the climate contribution of GI as discussed in the results, the overview of the literature has also revealed some problems requiring further investigation. In this section we will discuss the results to identify possible avenues of future study in terms of (a) geographic distribution, (b) diverse research topics in climate benefits, (c) consideration of multiple co-benefits and trade-offs, and (d) socio-cultural benefits with climate significance that were under-represented in the literature.

Firstly, the review has demonstrated that GI for climate mitigation and adaptation is a recently increasing field of research with most studies published in the last four years, largely dominated by countries from Europe, North America, and Asia (e.g. UK, USA, and China). Several factors could influence this limited geographic pattern including: (1) restriction of reviewed publications in English; (2) search keywords limited to GI explicitly reporting climate change-related benefits; (3) the country-based research interest in studying climate contribution of GI; (4) the different number of academics researching the topic across countries; and (5) the accessibility of publications. However, little is reported on the climate benefits of GI in countries from South America, Africa, the Middle East, South-East Asia and India. This can be problematic since the multitude of GI benefits on climate action and sustainable development is particularly important for cities with high populations located in these continents, which are severely affected by negative impacts of climate change and extreme weather events.

In addition, most articles concentrated on climate adaptation benefits, in particular, flood management and heat stress reduction. We identified relatively few studies on coastal protection, water scarcity management, and ecosystem resilience improvement, though studies on such benefits also exist without using the GI terminology. Thus, further investigation and future research is needed on: (1) evidence for the interactions between biodiversity conservation and GI-based climate action and their effectiveness; (2) the optimal combinations of different GI types and species considering trade-offs between heat stress reduction and water use requirement for irrigation especially in (semi-)arid climates; (3) comprehensively identifying performances and attributes of coastal GI schemes to reduce wave and storm surge impacts across different morphological and climatological site conditions (e.g. Schoonees et al., 2019).

For climate mitigation benefits, the literature has predominantly focused on direct mitigation of GI through carbon storage and sequestration, however, its indirect contribution through renewable energy opportunities, and promoting sustainable travel were scarce and merely discussed as co-benefits in a few articles. It is evident that more research is necessary to explore the opportunities of renewable energy provision and related co-benefits across multiple scales, for instance, through creative combinations of green and grey features at building scale (e.g. integration of solar panel in green roofs with wildlife habitats) and biomass energy production in urban agriculture and forests at the landscape scale, as well as promoting sustainable travel by increasing spatial connectivity between GI features, and the implications for mitigation and health/wellbeing issues.

Moreover, research was generally strongly focused on a single climate benefit, and associated co-benefits or trade-offs were often unrecognized or only implicitly discussed in the literature. Although multi-functionality represents the core principle of GI (Hansen et al., 2016), positive and negative links between benefits were largely identified only in a limited number of studies that examined a wide range of co-benefits or trade-offs. This can be problematic when interventions optimized to a single benefit result in unexpected outcomes or potential trade-offs in other sectors (Salmond et al., 2016). Hence, more research efforts are required to analyze the performance and to develop planning of various GI-based strategies in delivering multiple co-benefits and trade-offs for each climate benefit.

Lastly, though a large number of articles studied co-benefits with environmental values, few studies investigated or demonstrated the benefits concerning socio-cultural values (e.g. aesthetic/amenity and health/wellbeing). It is important, however, to study the social benefits of GI given their implications to climate change adaptation. For instance, environmental education can enhance public support for adaptation measures by providing information on GI to reduce local flooding and temperature (Derkzen et al., 2017). Strategically placed GI measures can provide communities with opportunities for environmental awareness, which leads to increased coping capacities to climate change (Garcia-Cuerva et al., 2018). Besides, environmental justice is another benefit that can contribute to the adaptive capacities of communities and individuals (Scott et al., 2016). GI measures with thermal benefits are often unevenly distributed in cities, with under-privileged communities with low-income and minority populations, who represent the communities most vulnerable to heat stress, potentially living in areas with low accessibility to green spaces (Pham et al 2012). If climate benefits of GI are detached from social demand and access to the benefits, GI might result in increased social injustice by offering benefits to certain groups of society with relevance and accessibility (Rodríguez et al., 2006; Hansen et al., 2016). Thus, research should be conducted into incorporating environmental justice issues into planning climate-conscious GI schemes by prioritizing vulnerable communities (Sharma et al., 2018).

4.2 Comparison with other studies

Our review is generally in line with some previous reviews that examine multiple benefits and types of GI. Demuzere et al. (2014) synthesized 86 papers on the adaptation and mitigation benefits of GI, which were classified into physical, and psychological and social benefits and explored positive links between the climate benefits with GI elements that favor the benefits. Although Demuzere et al. (2014) employed a different framework in categorizing climate benefits, for example, psychological and social benefits, partly equivalent to several of the co-benefits identified in section 3.4, they utilized a similar method in identifying the GI type-benefit and the interactions between benefits and suggested a relatively high level of positive links among thermal comfort and reduced energy use, flooding reduction, and CO_2 reduction, in line with our findings (section 3.3). They also identified several trade-offs including the negative impacts of trees on heat stress reduction, air quality improvement, and carbon emission reduction, also covered by our findings (section 3.5). However, our review systematically reviewed literature and presented a wider range of climate benefits, including coastal protection, ecosystem resilience improvement, and renewable opportunities, and a more comprehensive typology of the co-benefits, features, and trade-offs of GI. Also, this review presents co-benefits and types according to each climate benefit so that researchers/practitioners can find relevant information according to their topic of interest.

This study is also partly consistent with the results proposed by Kim and Song (2019), who analyzed the linkages between 12 GI features and 9 benefits with economic, socio-cultural, and ecological aspects based on 447 stormwater case studies collected by American Society of Landscape Architecture. Using a similar method to analyze the type-benefit relationships they offered evidence for the multifunctionality of GI in the project case studies, identifying the six most frequent types with multiple benefits – bioretention area, permeable pavement, grassed swales, rain gardens, curb cuts that allow runoff from the street and sidewalks to be directed into GI elements, and rainwater harvesting, most of which were equivalent to the GI features for flood management identified in section 3.3. However, there was a notable difference in identifying green roofs as the prevalent type with multiple benefits in our review compared to curb cuts, which are non-ecological (grey) resources considered GI (i.e. functional green), in the study by Kim and Song (2019) based on practical case studies. This could be because green roofs are not often considered as cost-efficient as other GI features (e.g. curb cuts) for stormwater management purposes due to high costs of installation and management (Nordman et al., 2018), thus not frequently implemented in practice compared to bioretention and grassed swales. Furthermore, they found multiple benefits in 65% of the project cases analyzed (compared to 23% of the academic literature in this review). The most frequent benefits were enhanced economic capacity such as property values and green job creation, followed by education/recreation, while our review found environmental-related benefits to be the most frequently studied, e.g. temperature reduction and water purification. It is difficult to make a rigorous comparison because the two reviews had different research topics (climate benefit vs stormwater management), research contexts and data, e.g. the project reports reviewed by Kim and Song (2019) mostly contained information on economic benefits such as the number of jobs created or cost-efficiency relative to grey infrastructure. However, the discrepancy in some specific findings is notable since it is mainly attributed to the material types reviewed, i.e. academic literature vs project case studies. This implies that GI research and practice may have different interests and goals. In this sense, increasing the consideration of economic aspects in academic research could have significant implications for practice. For example, a cost-benefit analysis of green roofs taking into account broader multifunctional benefits could demonstrate their higher cost-efficiency compared to alternative grey infrastructure options for stormwater management, and thus promote wider adoption of green roofs in practice.

4.3 Implications for environmental management

4.3.1. GI planning and design for multiple benefits

This review identifies many positive links between benefits, thus increasing the understanding of climate benefits and their potential co-benefits. However, particularly for practitioners, it is also pertinent to examine how such multiple benefits can be delivered in a spatially explicit way across various scales. As part of this study, we intended to gather data on generic attributes for promoting multifunctional (co-)benefits and to develop planning recommendations, but few papers explicitly mentioned such information. So, here we examine discussions presented by several authors to explore possible planning and design approaches that can foster multiple benefits and minimize trade-offs in practice.

According to Hansen et al. (2019), multifunctionality as a core GI concept can be pursued at different spatial levels: (1) planning principle of green spaces at the city or neighborhood scales, and (2) spatial arrangement in the design and management of green spaces at the site scale. In the context of land use planning, the concept has been considered as a principle for transforming land-use practices towards more multi-functional uses, instead of mono-functional ones, that simultaneously promote, for instance, nature conservation, recreational use and agriculture or forestry (Galler et al., 2015). Likewise, in the GI context, multifunctionality means that multiple environmental, socio-cultural, and economic values are strategically considered (Hansen et al., 2019). Combining different functions in order to use limited space more effectively is particularly important in urban areas, where green space is scarce, and even more so in compact cities (Ahern, 2011). Our typology can be utilized in spatial planning for multifunctionality at meso-to-macro scales by suggesting the possible sets of climate benefits and co-benefits to be considered as project aims from an early stage, and to be revisited during the analysis and planning stages. For strategic planning at larger scales, avoiding conflicts and managing trade-offs is even more critical because there are usually diverse sectors and stakeholders each with different interests. Thus, one solution to manage conflicts or trade-offs can be prioritizing specific benefits (e.g. giving weights) or differentiating primary and secondary benefits based on an analysis of stakeholder demands, or site analysis to identify deficient ecosystem services and benefits (Hansen and Pauleit, 2014; Alves et al., 2018). To promote beneficial solutions, GI planning has to aim at optimal outcomes for all of the parties involved or at least achieve a consensus on which are to be prioritized.

Multifunctionality on the site level concerns the design and management of green spaces, and to be specific, spatial arrangement to combine or balance different functions at the same location. This can be developed through three levels, using (i) horizontal, (ii) vertical, and (iii) temporal aspects (Ahern, 2011; Rode, 2016; Hansen et al., 2019). The delivery of multiple GI benefits discussed in section 3.3 and the typology (section 3.6) can be spatially achieved by designing a site area (e.g. parks) using the following concepts with illustrative examples of benefits as identified in our review:

(i) horizontal use of space

(a) tessellated multifunctionality with spatial segregation of functions in one area (e.g. separating different land units for recreation, wildlife habitats, and rainwater retention in a park)

(b) partial multifunctionality by combining functions at the same location (e.g. lakes implemented for stormwater retention in a park, providing habitats and recreational co-benefits)

(c) total multifunctionality with an equal balance of different functions within an area (e.g. green roofs. integrated with solar panels simultaneously providing cooling, habitats, and renewable energy generation)

(ii) vertical stratification, mixing functions in the vertical dimension (e.g. utilizing powerline corridors for recreational and biodiversity conservation purposes by using ground area for GI functions underneath the power line (grey infrastructure function)

(iii) temporal phasing by promoting different functions at different moments in time (e.g. utilizing parks for. temporary stormwater retention during rainy seasons)

The above-mentioned concepts can also help deal with trade-offs through spatial arrangement at a site scale. For example, when designing a park to accommodate two possibly competing benefits (recreation/tourism and biodiversity conservation), practitioners might use (a) tessellated multifunctionality to segregate areas for each benefit and limit visitors of a day, or (iii) temporal phasing to allocate certain periods in a year to allow visitors to a park primarily implemented for habitats provision.

4.3.2 Informing planning and management decisions

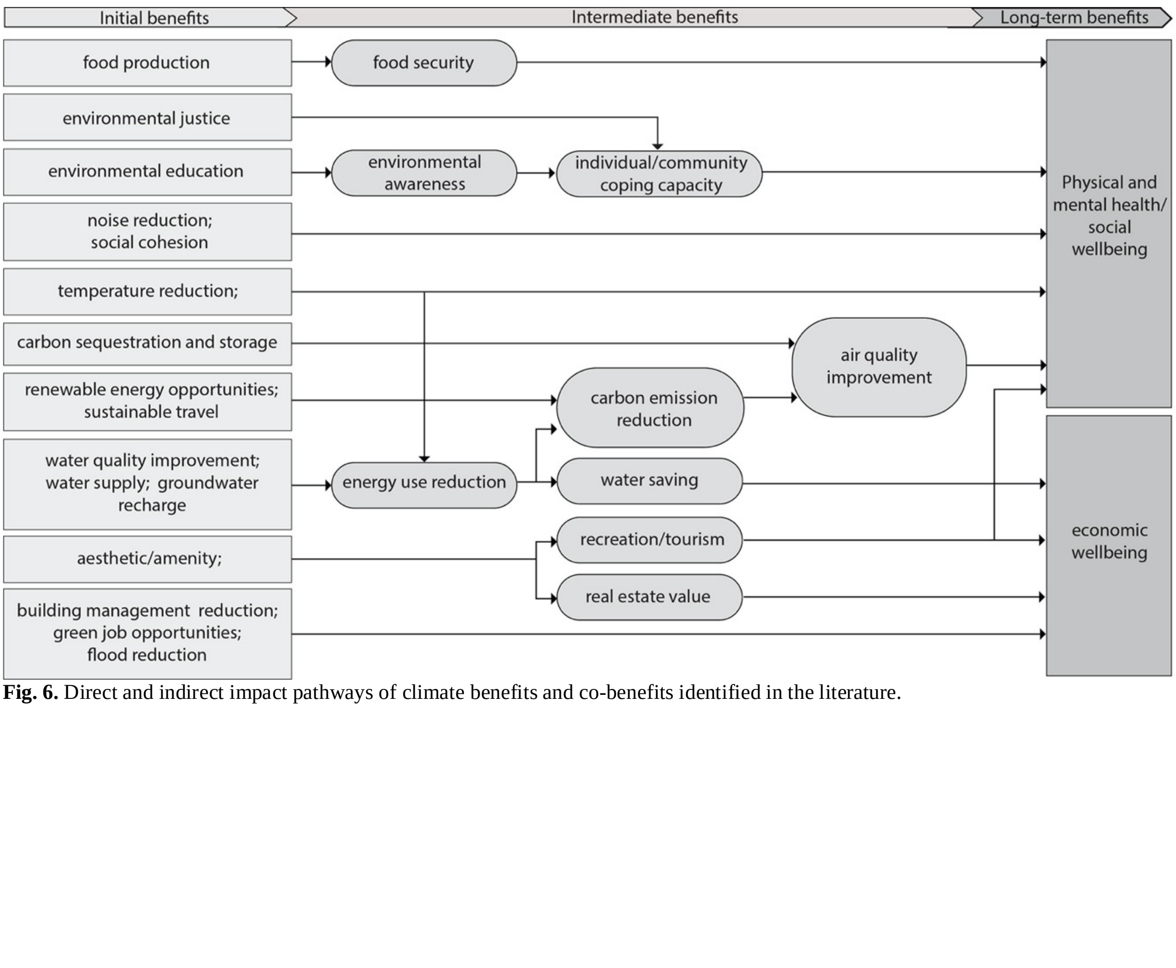

Fig. 6. Direct and indirect impact pathways of climate benefits and co-benefits identified in the literature.

This review provides a comprehensive evidence base from academic papers that can be used to demonstrate the value of GI to stakeholders and decision-makers across an extensive range of climate co-benefits. Despite the potential benefit of GI for climate action and sustainable development, stakeholders and decision-makers might not choose GI-based strategies due to uncertainties around costs and benefits of GI (BenDor et al., 2018). Although the estimation of benefits was not analyzed directly, inferred evidence from academic literature can provide some basic information on the multitude of benefits to stakeholders and decision-makers. Moreover, our typology of links between GI strategies and their benefits would guide GI researchers and practitioners to select relevant features for maximizing co-benefits while minimizing undesirable trade-offs, and to explore impact pathways by which different benefits affect each other from initial to long-term stages in research, policy and practice for sustainable development.

Categorizing multiple services and benefits of GI is complicated because of their complex interactions and potential causalities. During the study, we identified some of the direct and indirect (causal) relationships between a wide array of benefits based on the reviewed studies as illustrated in Figure 6 from initial through to later stages. For example, forests can provide carbon storage and sequestration benefit, leading to improved air quality and this results in improved human health/wellbeing due to reduced risks of respiratory disease. Likewise, improved water quality provided by vegetation and soil filtration of bioretention can reduce energy use in wastewater treatment plants, decreasing water usage required for electricity generation and associated social costs, at the same time, reducing carbon emissions from fossil fuel-based plants, which linked to air quality improvement and health/wellbeing benefits in the end. However, this is not comprehensive, and a more holistic review is still needed for a better understanding of the pathways among inter-related multiple benefits.

5. Conclusions

Climate change poses an increasing threat to natural and human systems. The benefits provided by GI can help adapting to and mitigating climate change. This review has synthesized the evidence of 141 papers on the contribution of GI to climate adaptation and mitigation. Previous studies examining the linkages between the multiple benefits of GI have been limited to certain types of ecosystem services and benefits (e.g. flood risk reduction), or GI features (e.g. trees), often ignoring associated disservices or trade-offs (Roy et al., 2012; Demuzere et al., 2014; Kim and Song, 2019). By systematically reviewing the literature, this study has investigated not only the co-benefits and trade-offs for each climate benefit, but also bundles of major co-benefits and GI features, based on the number of papers presenting evidence for each link. This enables a comprehensive overview of the role of GI in delivering adaptation and mitigation benefits, which underpins the typology we developed. The findings of this study can be used by researchers and practitioners to identify opportunities to deliver multiple ecosystem services and benefits whilst recognizing disservices and trade-offs that need to be avoided or managed.

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