Urban Forestry & Urban Greening 94 (2024) 128262

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

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

Trade-offs and synergies in urban green infrastructure: A systematic review

Baige Zhang [*], Andrew MacKenzie

Fenner School of Environment & Society, Australian National University, Australia

ARTICLE INFO

Handling Editor: Dr Cecil Konijnendijk van den Bosch

Keywords:
Ecosystem disservices
Ecosystem services
Green Infrastructure
Synergies
Trade-offs

ABSTRACT

The incorporation of green infrastructure (GI) into urban systems has emerged as an important climate change mitigation and adaptation strategy. The rationale for incorporating GI is based on the premise that ecosystem services (ESs) supplied by GI significantly improve the liveability and resilience of urban systems to natural hazards. However, research has also highlighted the presence of ecosystem disservices (EDs) associated with GI. To optimise the delivery of ESs outcomes, research has sought to explore the interrelations between ESs and EDs supplied by GI through a better understanding of trade-offs and synergies. This paper presents a review of 96 case studies globally of the interrelations between ESs and EDs provided by GI in urban areas. The results show that relationships between ESs and EDs are variable and highly context-dependent in relation to the characteristics of GI components, biophysical conditions, and the perceptions of local stakeholders. The conventional approach of bundling ESs to analyse correlations between them does not adequately capture these complex relationships, making it difficult to predict optimal outcomes for GI investment. We suggest that analysing the functional traits of GI is a more effective approach to explore the causation of trade-offs and synergies. This would provide a more robust and nuanced understanding of the dynamic relationships between ESs and EDs and facilitate GI parameterisation for optimising benefits. Policymakers and planners could integrate this biophysical assessment with socioeconomic information in guiding GI planning to provide the most effective ESs outcomes while minimising EDs.

1. Introduction

The integration of Green Infrastructure (GI) into sustainable development strategies has become commonplace in urban planning, owing to its promising contribution to urban liveability through improving human physical and mental well-being (Chatzimentor et al., 2020; Lin et al., 2019). GI is commonly defined as the networks of natural and semi-natural elements incorporated into the city fabric (Benedict and McMahon, 2006; European Commission, 2013; Naumann et al., 2011). GI concepts and practice have been adopted flexibly by a wide range of disciplines, such as urban forestry, environmental science, and epidemiology, along with urban planning, landscape architecture and urban design, encouraging researchers to broaden its scope to reflect a wide variety of applications (Albert and Von Haaren, 2017; Wright, 2011).

Notwithstanding the diverse and wide-ranging definitions and applications of GI, its efficacy is predominantly evaluated by its capacity to deliver Ecosystem Services (ESs). ESs refer to the ecological characteristics, functions, or processes that contribute to human well-being (Costanza et al., 1997). There has been a notable increase in the use of this term since the release of the Millennium Ecosystem Assessment (MEA, 2005). Although it did not initially refer to ESs in urban contexts, this has subsequently changed due to its relevance in urban environments (Cilliers et al., 2013; Haase, 2015). However, it is equally important to acknowledge the potential negative impacts of GI, known as ecosystem disservices (EDs) (Lyytimäki and Sipilä, 2009). Although the detrimental consequences stemming from ecosystems are not newly detected, systematic research on EDs is at its inception when compared to the extensive body of ESs literature (von Döhren and Haase, 2015). Nevertheless, there is a growing acknowledgement of the significance of comprehending EDs in anthropogenic landscapes, particularly in urban ecosystems (von Döhren and Haase, 2015). The novel urban ecosystems have redefined the human-nature relationship (Ahern, 2016), placing a high priority on the investigation of EDs, which has the potential to counteract the design of GI intentionally aimed at enhancing human health and well-being.

Achieving optimal GI outcomes necessitates a comprehensive understanding of the complex interrelations between ESs and EDs, otherwise known as trade-offs and synergies. The term “trade-off” originated

* Corresponding author.
E-mail address: Baige.Zhang@anu.edu.au (B. Zhang).

https://doi.org/10.1016/j.ufug.2024.128262
Received 5 June 2023; Received in revised form 8 February 2024; Accepted 18 February 2024
Available online 20 February 2024

from economics, where it is explained in terms of society's production-possibility frontier (Samuelson, 1970), and has been explored in various fields, like risk management (Tuhkanen et al., 2018) and urban planning (McShane et al., 2011). In the GI literature, the trade-off analytical framework was initially employed to identify the negative correlations between spatial or temporal co-occurrences of ESs supplies (Bennett et al., 2009; Mouchet et al., 2014; Rodríguez et al., 2006). More recently, this framework has been expanded to incorporate EDs, also denoting a positive association between a service and a disservice (Roman et al., 2021). Synergies, conversely, represent the inverse relationship of trade-offs (Bennett et al., 2009; Roman et al., 2021), and describe a reversal in the impacts on two ESs, or a positive association between a service and a disservice. To more precisely capture the direction of change, synergies are further categorised as win-win scenarios (positive synergies), where ESs increase while EDs decrease, and lose-lose scenarios (negative synergies), the contrary circumstance to positive synergies (Roman et al., 2021).

Understanding the interrelations between ESs and EDs underpins effective GI implementation to achieve multiple objectives in urban planning. Optimising positive synergies can potentially increase the efficiency and performance of GI, whereas unintended trade-offs might result in suboptimal service delivery or additional socioeconomic burdens (Depietri, 2022). However, trade-offs and synergies have not been systematically assessed in urban ecosystems.

Previous analysis of trade-offs and synergies has been disproportionately centred on agricultural and natural ecosystems (Howe et al., 2014; Ndong et al., 2020; Spake et al., 2017). This research focus has impeded the comprehensive understanding of the dynamics within the context of novel urban ecosystems. GI, characterised by distinct species compositions and configurations, may shape ESs and EDs relationships differently in comparison to its natural counterparts. In addition, the interactions between ESs and EDs involve not only GI elements but also stakeholders, whose diverse demands challenge frameworks developed exclusively for biophysical factors (Kronenberg et al., 2021).

Promotion of GI adoption through advocacy of its "multi-functionality" often considers GI as a boundary object and assumes that synergies are inherent among its multiple functions. However, prior urban studies have identified the distinctive capacity of ESs provision with different GI elements and identified that the benefits are not necessarily synergistic (Choi et al., 2021; Smith et al., 2017). To gain a deeper understanding of the mechanisms governing trade-offs and synergies, it is imperative for researchers to closely examine GI at the unit level rather than treating it as a novel abstraction.

Furthermore, current analytical frameworks applied in urban contexts rarely incorporate EDs (Chang et al., 2021; Meerow, 2020), despite the growing body of urban research that has illuminated the detrimental impacts emanating from ecosystem processes. Thus, the exploration of the connections between GI elements and EDs remains largely uncharted territory. This deficiency in research further hinders the holistic comprehension of the relationships, which could otherwise inform better GI design and implementation. To bridge the knowledge gap, this systematic review addresses the following questions, focusing specifically on GI:

1) How are ESs and EDs related, and associated with GI elements in urban settings?

2) How do exogenous and endogenous factors influence the relationships between ESs and EDs?

3) What methods are used to investigate trade-offs and synergies between ESs and EDs in urban settings?

By exploring these questions, this review sheds light on the current state of knowledge of urban GI approaches and future research directions. The next section introduces the methods used for data collection and synthesis. The results section describes the data analysis in terms of overall trends, linkages between GI elements, ESs and EDs, the factors that affect trade-offs and synergies, and the state-of-the-art methods used for relationship analysis. We then propose a framework based on functional trait-service relationships to better facilitate GI implementation. Finally, the paper concludes with key findings and recommendations for future research.

2. Methods

2.1. Systematic literature review

This study was conducted as a systematic literature review, which has the advantages of searching a broad range of articles, allowing for mapping research trends, and identifying gaps and uncertainties in the domain of enquiry (O'Brien and Mc Guckin, 2016). The main steps adopted by this study, drawing from relevant theoretical frameworks (Moher et al., 2009; Pickering and Byrne, 2014) and examples (Choi et al., 2021; Smith et al., 2017), are summarised in Fig. 1. To ensure the review is extensive and exhaustive, a snowballing method was utilised, whereby the original source of cited literature was also examined (Mouton and Babbie, 2001).

The literature searching and screening were undertaken from June to December 2021, with updates incorporated in February 2024. The phrases ("Urban") AND ("Green Infrastructure") AND ("Trade-offs" OR "Synergies") were searched in titles, abstracts, and keywords from three databases: Google Scholar, Scopus, and Web of Science, without time-span restrictions. Initially, 207 articles were retrieved from the databases, and after removing duplicates, inaccessible links, and non-peer-reviewed articles, 122 studies remained for screening of abstracts. The screening process eliminated studies not written in English and non-original research, as target articles were limited to empirical studies to avoid double counting the cases. The full texts of the remaining articles were scrutinised based on the following criteria: 1) within identifiable GI elements, 2) explicit links between GI elements and ESs and EDs, and 3) information on trade-offs or synergies between ESs and EDs. During this stage, irrelevant studies excluded were mainly those regarding GI as a conceptual innovation to facilitate investment, policymaking, and knowledge exchange rather than tangible biophysical expressions that deliver ESs and EDs. A snowballing method was used to broaden the dataset, starting with the reference lists of both the selected articles and some excluded studies. A further 46 relevant papers were added at the final stage for in-depth analysis.

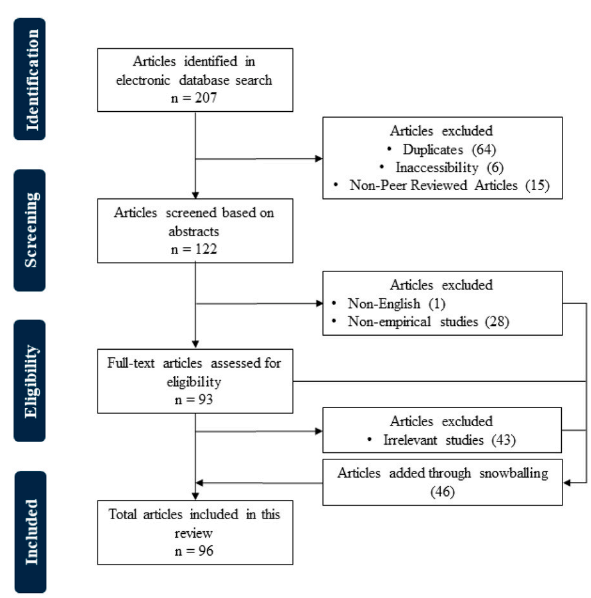


Fig. 1. Overview of literature search and article selection, Note: adapted from Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al., 2009).

2.2. Data extraction and analysis

Data extraction was framed primarily around trade-offs and synergies between different ESs and EDs. ESs were firstly classified according to the Common International Classification of Ecosystem Services (CICES), through which services are categorised into three groups, provisioning, regulating and maintenance, and cultural (Haines-Young and Potschin, 2018). This study added the frequently-reported services of social capital enhancement and a sense of place, as none of the equivalent classes was found in the CICES (Haines-Young and Potschin, 2018). Given the variability in the typology of EDs across different studies, disservices were recorded directly and roughly accommodated into the ecological, economic, health, and psychological categories as suggested by von Döhren and Haase (2015).

The relationships between ESs and EDs were documented as trade-offs or synergies according to the expanded analytical framework. In each case study, the occurrences of either relationship were counted. Multiple counts were allowed for articles with various pairs of ESs and EDs. However, the same relationship for the same pair was counted only once within each case. Given the variability of the relationships, the probability of trade-offs and synergies and robustness were calculated based on the counts, following Pan et al. (2022):

$$Probability = \frac{NoT \quad or \quad NoS}{NoTI}$$

$$Robustness = 1 - \frac{1}{NoTI}$$

where NoT and NoS are the number of trade-offs and synergies reported, respectively, while NoTI is the number of total interrelations reported by case studies.

Probability denotes the prevailing pattern of the relationship. Generally, a high probability indicates a strong inclination toward a particular interrelation, and the sum of the probability of trade-off and synergy equals one. For example, a 30% probability of a trade-off indicates a 70% likelihood of synergy occurring in the full set of all cases. Robustness signifies the reliability of the probability. The value of robustness increases with the number of reported interrelations, implying a more consistent and stable relationship, especially when the probabilities are the same.

The following additional information was also recorded for each article: 1) the year of publication and locations and climates of the study sites, 2) GI elements, 3) the linkage between GI elements and ESs or EDs, 4) the factors underpinning trade-offs and synergies, and 5) the methods used for relationship analysis.

The locations were documented by city names, and grouped by countries and continents, while the climates were recorded based on the Köppen classification. GI elements were characterised along the green-grey infrastructure continuum, comprising natural green (e.g. forests and waterbodies), engineered green (e.g. green roofs and walls), and functional green (e.g. permeable pavements and cycling paths) (Mell, 2013). The linkages indicating relationships among GI elements and different ESs and EDs were recorded by the vote-counting approach and descriptive statistics based on the frequency of citations (Choi et al., 2021; Smith et al., 2017). The results reflect only the number of links providing the evidence that such a relationship exists, rather than its strength. Similarly, the absence of numbers does not indicate a non-association, but there is none or little evidence identified from the articles reviewed (Choi et al., 2021). Additionally, the factors affecting trade-offs and synergies and the methodologies for assessment were summarised from each of the studies.

3. Results

3.1. Overview of GI studies on trade-offs and synergies in cities

It is evident from the review that the analysis of trade-offs and synergies is a burgeoning field in GI research. While less than a decade ago, spatial analysis of interrelations between ESs and EDs was still in its infancy (Hansen and Pauleit, 2014; Sussams et al., 2015), a substantial number of articles have been published recently. Approximately 65% of all studies were published in the last five years and over 90% in the last decade. The examination of trade-offs and synergies did not become the central theme of case studies until 2013, although the earliest article included in this review, implying direct interactions between carbon sequestration and temperature mitigation (Nowak and Crane, 2002), was published in 2002. However, such interactions were rarely interpreted as trade-offs or synergies during the early period, and rather the terms co-benefits or ancillary benefits were used instead to describe the synergistic relationship. Despite the recent increase, the analysis of ESs-EDs relationships still constitutes only a small proportion of the overall GI literature.

This research also reveals a distinct geographic and climatic distribution of the study sites, with the majority concentrated in Europe (43%), North America (26%), and Asia (18%). A country-based classification suggests that the United States (22%) dominated the research efforts with the highest number of case studies, and the top four countries (The United States, China, Germany, and the United Kingdom) contributed to around half of the total research, whereas the remaining 31 countries included in this review shared the other half. Given the larger base of GI publications in these countries (Parker and de Baro, 2019), the national disparity is unsurprising. Despite calls for more research in cities of the Global South, which are predicted to experience massive urbanisation in the near future and thereby have greater potential for GI implementation (Cheshmehzangi et al., 2021), this gap remains unfilled so far. In addition, although case studies were conducted in 112 cities globally, the temperate oceanic climate (Cfb, 32%) and the humid subtropical climate (Cfa, 20%) accounted for more than half of the total sites. Considering the influences of national policies on GI strategies and that of climates on ESs and EDs provision, this reporting bias is likely to distort the ESs-EDs relationship analysis towards dominant case study countries and climatological environments.

3.2. Linkage between GI elements and associated ESs and EDs

Among the 16 elements of GI recorded, green space was studied with the highest frequency, primarily because of its multifunctionality, as it contains other units (e.g. trees and grassland) as well as the corresponding ESs and EDs. Additionally, the majority of research was conducted at the municipal or larger statistical unit level where green open space is the finest-scale meaningful unit to assess. Notwithstanding proposals to broaden the definition of GI to cover technical systems (e.g. solar panels) with 'greening' functions in spite of their non-green visual appearance (Mell, 2013), there are more studies relative to natural and semi-natural GI components for the following reasons: technical GI is generally more complex with fewer identified uses; more complex systems are limited by cost and skills, especially in developing and underdeveloped cities (Cheshmehzangi et al., 2021); and researchers often assessed the dominant function rather than the multifunctionality of these artificial systems, overlooking the interrelations between multiple ESs and EDs.

A total of 26 ESs and EDs were identified in this review. The regulating and maintenance service clusters accounted for the largest share in the case studies, which is expected, given the key contributions to urban liveability that the regulation and maintenance ESs make to human health and well-being. On the other hand, cultural services were less studied due to the difficulties in quantification (Cheng et al., 2021), as the magnitude of cultural services depends not only on the ecosystem process but also on the values of recipients, which are subjective. Provisioning services were least studied in urban areas since cities often import such services from the surrounding non-urban regions (Brzoska and Spāġe, 2020). Nonetheless, a growing number of researchers advocate for the study of provisioning services to promote urban agriculture, urban foraging, and edible urbanism as a means to reduce ecological footprints while improving food security and resilience in cities (Russo and Cirella, 2019; Säumel et al., 2019). One-third of articles investigated EDs substantially less than ESs, reflecting the enthusiasm for the pursuit of benefits as one of the primary objectives of GI implementation; this overshadows concerns for potential detriments. As a result, the underestimation of disservices might be problematic, as stakeholders may misrepresent multiple benefits of GI by under-reporting certain environmental nuisances (Kirkpatrick et al., 2012).

This research seeks to quantify the frequency of linkages of ESs and EDs, and identify the association of trade-offs and synergies with GI

Table 1
The number of studies linking the trade-offs and synergies with GI elements (adapted from Mell, 2013).

Green-grey Continuum
Natural Green — Engineered Green — Functional Green

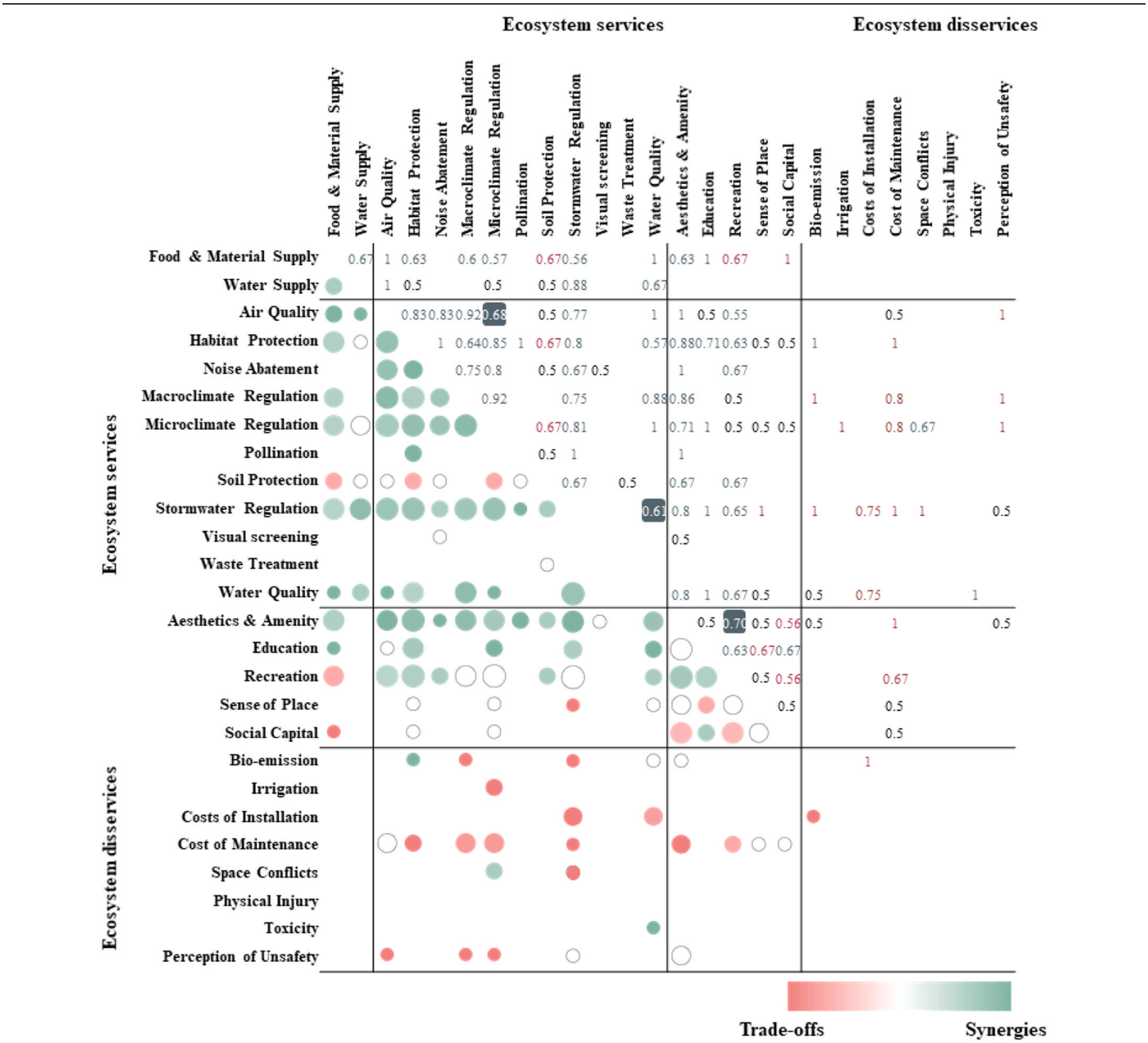
		GI elements	Farmland	Grassland	Individual Tree	Shrubs	Soil	Urban Forest	Waterbody	Bioswales	Community Garden	(Constructed) Wetland	Green Roof	Green Space	Green Wall	Permeable Pavement	Recreational Facilities	Total number of studies
Ecosystem services	Provisioning	Food & Material Supply	3	1	3	1	1	3	2	1	1	1	2	8				20
			1	1	2			2	2	1			2	7				
		Water Supply							3		1	3	2	4		2		13
										3	1	2	3	2		1		
	Regulating & maintenance	Air Quality		1	3	3		4			2		2	10	2			28
				1	4	2		10		2	2	1	3	12	4	3		
		Habitat Protection	1	1	2	1		6	2		2	5	2	14	2		1	37
			1	2	3	1	1	12	5	1	2	6	2	19	3	1	1	
		Noise Abatement			2	1		1			1		1	2	1			8
					2	2		3			1			5	2			
		Macroclimate Regulation		1	6	3	3	5	2		2	2	1	10	1			30
				2	8	2	4	8	3	2	2	1	3	10	1	3		
		Microclimate Regulation		1	5	3		4	4		4	2	5	14	3			38
				1	7	2		9	4		1	2	4	12	5	2		
		Pollination						1			1		1	3				5
						1		1			1			4	1			
		Soil Protection			1	1		1			1		1	5				7
								2			1		1	4				
		Stormwater Regulation	3	2	5	4	1	4	6	10	2	3	7	12		4	1	50
				1	1	2	2	5	9	9	2	10	8	15		5		
		Visual screening			2			1							1			3
					2			1										
		Waste Treatment											1	1				1
														1				
		Water Quality		1	1	2	1	1	5	6	1	4	3	3		4		27
				1	1	1	2	2	7	7		6	5	2		3		
	Cultural	Aesthetics & Amenity	1	3	2	1		4	3	2	1		2	15	1			35
			1	2	3	3		5	4	1		2	2	17	2		1	
		Education							1					6			1	12
								1	2	1			1	5			1	
		Recreation		1	2	1	1	4	3		3	1	2	21			2	34
				1	1	1	1	5	7	1	1	2	2	22		1	1	
		Sense of Place				1				1				5				7
						1				1				3				
		Social Capital						2	1	1				6				7
														5				
Ecosystem disservices	Ecological	Bio-emission								1		2	1	1		1		6
					1				1			2		1				
		Irrigation			1								1	3				5
														1				
	Economic	Costs of Installation								3		1	2		1	3	1	8
										1							1	
		Cost of Maintenance		2	3	1		1	2	1			1	3	1			12
				1	1		1							1	1			
		Space Conflicts	1		2			1	1	1				2				6
					2					1								
	Mental Health	Physical Injury			1													1
					1													
		Toxicity								1			1			1		3
									1	1						1		
		Perception of Unsafety		1	1	1		1						3				5
								1						3				
		Total number of studies	4	4	17	7	5	20	15	16	6	15	15	41	5	7	2	96

elements. Table 1 summarised the outcomes, where the x-axis classifies GI elements along the green-grey infrastructure continuum (Mell, 2013), while the Y-axis lists ESs and EDs supplied by these GI elements. The red cells indicate associations involving trade-offs, while the green cells identify synergistic associations. The number in each cell represents the ESs and EDs that were recorded by the vote-counting approach and descriptive statistics based on the frequency of citations (Choi et al., 2021; Smith et al., 2017), with more frequently cited links highlighted in darker shades. The results demonstrate a close association between GI elements and ESs and EDs supply. Consequently, implementing suitable GI elements is key to meeting specific ES demands or avoiding particular disservices. However, multiple ESs and EDs provided by the same GI elements do not necessarily have a single relationship, as the red and green cells coexist in most associations. This challenges the notion of "multifunctionality" because synergies among multiple ESs are not always guaranteed. The results emphasise that the selection of GI elements is not the sole determinant of trade-offs and synergies, suggesting the presence of other influencing factors.

3.3. Trade-offs and synergies between ESs and EDs

Results of this review support prior findings that the relationships between ESs and EDs are variable and non-linear (Bennett et al., 2009; Raudsepp-Hearne et al., 2010; Rodríguez et al., 2006), as divergent relationships between pairs of ESs and EDs were reported in different cases. Table 2 summarised the probability and robustness of the relationships by using colour-coding to indicate whether these ESs and EDs were more likely interrelated with trade-offs (in red) or synergies (in green). The figures represent the probability of the interrelations, while the size of the circles indicates the robustness. Relationships reported only once were excluded because the robustness values equalled zero. Relationships with robustness values greater than 0.95 are highlighted

Table 2
Trade-offs and synergies between ESs and EDs.



in dark shades.

Overall, trade-offs were more likely to occur between a single service and a disservice. This was particularly true when operational factors, such as the high installation costs for engineered and functional green units (Alves et al., 2020), the increased maintenance demands of trees and grassland (Oldfield et al., 2015), or conflicts of land use for other developing purposes (e.g. real estate and grey infrastructure) (Erlwein and Pauleit, 2021), were taken into account during ESs evaluation. Few trade-offs occurred among regulating and maintenance ESs, except for soil protection, which was associated with lower habitat value and reduced capacity to moderate microclimate. Although some researchers have suggested that cultural services are generally supplied synergistically (Daniel et al., 2012), optimal outcomes were not – as the examples below illustrate – necessarily equitably consumed, raising concerns about access to ESs and other environmental justice issues. For example, the uneven spatial distribution of ESs supply can dampen social capital by increasing inequity (Escobedo et al., 2015; Walker, 2021). Amorim et al. (2021) noted that urban parks with high aesthetic and recreational values are more likely to lead to green gentrification which accelerates social stratification.

Synergies between various ecosystem services were widely reported in the literature. In contrast to previous research that has found trade-offs often associated with provisioning ESs (Hossu et al., 2019), several studies have demonstrated that GI can provide food, improve stormwater quality, and support other services in a compatible manner (Grard et al., 2018; Well and Ludwig, 2021). While a few studies illustrated the synergistic relationship between a service and a disservice, negative synergies (also characterised as a "lose-lose" scenario), where ESs are reduced and EDs are amplified (Haase et al., 2012; Roman et al., 2021), were reported more commonly. For example, high input maintenance on grassland could decrease its capacity for carbon sequestration (Kong et al., 2014), and in another case, the costly installation of pedestrian and cycling paths resulted in the degradation of wildlife habitats (Abramowicz and Stępniewska, 2020).

3.4. The factors underpinning trade-offs and synergies

Previous studies have summarised two mechanisms that drive the relationships between ESs and EDs, leading to trade-offs and synergies: direct interactions and indirect associations (Bennett et al., 2009; Birkhofer et al., 2015). However, this review found that the mechanisms of interrelation are not the basic determinant of the relationship, as contrasting relationships were observed from the interaction between the same pair of ESs. For instance, the cooling effects of GI could enlarge the temperature gradient, promote convection, and disperse air pollutants, resulting in a synergistic relationship as reported in Seoul (Baik et al., 2012); however, the strengthened bay breeze brought ozone precursors to Baltimore and exacerbated the poor local air quality because of its specific geographic location (Loughner et al., 2012).

Instead, this review identifies that trade-offs and synergies are determined primarily by the magnitude of ESs and EDs supply, which is subject to the characteristics of GI (e.g. components, composition, and configuration) and the contexts (e.g. geographic, hydrological, and meteorological conditions) where the GI components are deployed. For example, Tran et al. (2020) illustrated that different traits of vegetated GI could lead to certain trade-offs or synergies among eight ESs, and Cuthbert et al. (2022) demonstrated the trade-off between water retention and cooling effects of urban parks and green roofs driven by different climatic conditions.

Furthermore, stakeholder perceptions can play a crucial role in shaping relationships between ESs and EDs. Hossu et al. (2019) identified varying trade-offs and synergies perceived by residents, visitors, and experts, which can be attributed to differences in stakeholder values and priorities. Demographic characteristics, such as age, gender, income, ethnicity, occupation, education, and property ownership, have been linked to stakeholders' attitudes, preferences, and priorities (Ode Sang et al., 2016; Riechers et al., 2017; Suppakittpaisarn et al., 2019). Personal characteristics and experiences have also been found to influence stakeholder perceptions (Conway and Yip, 2016; Kirkpatrick et al., 2013). Nevertheless, few studies have considered the diversity of stakeholders in the analysis of trade-offs and synergies, and ESs and EDs evaluation has primarily relied on average social norms and value orientations (Plieninger et al., 2013).

3.5. Approaches to the analysis of trade-offs and synergies

This review observed that the analysis of trade-offs and synergies lacks standardised approaches. In studies involving few ESs and EDs (often less than three), research has mainly focused on changes in the magnitude of supply rather than the interrelations. However, ESs bundling was commonly used when analysing multiple ESs and EDs. In conjunction with spatial analysis, ESs bundling has been widely integrated into various models, such as Green Infrastructure Spatial Planning (GISP) (Meerow and Newell, 2017) and Bivariate Local Indicator of Spatial Autocorrelation (BiLISA) (Chang et al., 2021), to map the interrelations between ESs based on cluster analysis (Spake et al., 2017). Statistical methods, such as Pearson's bivariate correlations, have also been employed to further classify the relationships. Despite the widespread use of ESs bundling, little attention has been given to EDs research, which may be attributed to the nature of research projects rather than the methodology *per se*. ESs bundling can exhibit spatial dynamics and in doing so provide a better understanding of environmental inequity. However, previous studies have highlighted several methodological shortcomings. Ndong et al. (2020) argued that most studies have assessed ESs clusters using a snapshot approach, which fails to illuminate the temporal dynamics of ESs and EDs supply, thus limiting the ability to evaluate the long-term benefits of GI. Fusaro et al. (2015) suggest the incorporation of vegetation phenology that considers seasonal changes and spatial influences, and adjusting the general models on this basis. Furthermore, the use of statistical correlations only displays pattern-based relationships and fails to explain the mechanistic process of causation (Bennett et al., 2009). Simply interpreting negative correlations as trade-offs and positive correlations as synergies can be problematic when considering how ESs and EDs are generated and consumed (Crouzat et al., 2015).

Spake et al. (2017) further argue that the ESs-EDs relationships are largely determined by the inputs, which are based on the subjectivity of researchers. First, the current indicator-based assessment approaches are usually coarse, with Land Use and Land Cover (LULC) commonly used for ESs and EDs estimation, while internal heterogeneity (e.g. species composition and configuration) was largely ignored. Second, the indicators were rarely standardised and integrated with stakeholders' perceptions. Using different indicators for assessment can lead to ambiguity, particularly for habitat value, where the abundance or richness of different species is diversely used. High-quality habitats for one species may not be the same for another, and natural and managerial interventions can have opposite effects on different wildlife (Reed and Merenlender, 2008). On the other hand, these diverse indicators have different implications in contributing to human health and well-being, as evidenced by studies that found a positive relationship between psychological benefits and bird species richness (Fuller et al., 2007), while plant richness was associated with a decrease in wellbeing (Dallimer et al., 2012). These findings underscore that place-based GI planning requires more tailored and standardised methods to ensure effective and equitable management of ESs and EDs (BenDor et al., 2017; Hansen et al., 2019).

4. Discussion

4.1. An alternative approach in trade-offs and synergies analysis

This paper proposes that analysing trade-offs and synergies between

ESs and EDs can benefit from incorporating the functional trait-service relationship, which offers a more comprehensive and nuanced understanding of the dynamic relationships between ESs and EDs. The importance of investigating the trait-service relationship has been recognised for over a decade (de Bello et al., 2010). However, functional traits of GI have found more frequent applications in phenotyping (Fiorani and Schurr, 2013), ecosystem monitoring (Bussotti and Pollastrini, 2015), and ESs mapping and modelling (Fusaro et al., 2018; Lavorel et al., 2011). Its utilisation in trade-offs and synergies analysis has only recently gained attention in the scholarly literature (Hanisch et al., 2020; Pan et al., 2022).

Functional traits including the morphological, chemical, physiological, and symptomatic attributes of GI elements provide demonstrable links to ecosystem processes (Bussotti and Pollastrini, 2015). Functional traits inherently encapsulate trade-offs among different functions within an organism from the ecophysiological and evolutionary perspectives (de Bello et al., 2010). For instance, Bussotti and Pollastrini (2015) illuminated the trade-offs between photosynthesis-related functions (e.g. carbon storage) and water-balance-related ESs (e.g. microclimate regulation) by investigating leaf traits of forest trees. It is a persistent dilemma faced by plants, wherein resources must be decided on whether to allocate towards traits that enhance photosynthesis or those that bolster drought defence strategies. In contrast to land cover-based assessments, the functional trait-based approach provides an in-depth examination of the mechanistic processes underpinning the generation of ESs and EDs, which informs the causation underlying trade-offs and synergies (Cebrián-Piqueras et al., 2021; Lavorel et al., 2011). In essence, the trait-based approach is accompanied by bioecological explanations, moving beyond the mere establishment of relationships based on statistical correlations. For example, when considering tree height as a functional trait, it is possible to rationally deduce the potential trade-off between microclimate amelioration and fire risk. Trees with lower trunk height shade a point for a longer time leading to cooler temperatures (Helletsgruber et al., 2020) yet may increase the vertical propagation of wildfires (Cruz et al., 2012). Moreover, this approach is scalable, facilitating assessments of GI performance at various levels. At the site scale, it permits the evaluation of individual GI elements based on the morphological, physiological, and biochemical features (Cameron and Blanuša, 2016). On a regional scale, this approach enables the expression of trait values' distribution within a community through specific metrics (Mason et al., 2005). The commonest metric calculates traits as the community-weighted mean value, following the biomass ratio hypothesis (Grime, 1998; Violle et al., 2007). Additionally, demographic traits, such as trait richness, evenness, and diversity, can be further incorporated into the assessment (Brown and Anand, 2022).

Despite the notable advantages of the trait-based approach, the knowledge of the linkage between functional traits and ESs and EDs remains limited (de Bello et al., 2010). This knowledge gap is particularly pronounced in the context of EDs. Functional traits can be further classified as those influencing the responses to environmental conditions (response traits) and those affecting the ecosystem functioning (effect traits) (Díaz et al., 2013; Violle et al., 2007). While the assessment of ESs delivery has often centred on effect traits, EDs have been conspicuously underrepresented in such evaluations. Future research efforts should place greater emphasis on exploring the connections between EDs and response traits, as many EDs arise from ecosystem vulnerabilities, such as bio-emissions triggered by both biotic and abiotic stressors (Fitzky et al., 2019).

Furthermore, the accuracy and independence of using functional traits for estimating the magnitude of ESs and EDs have been called into question (Lanta et al., 2011; Plas et al., 2020). On the one hand, a single ES might be more effectively described by a collective set of traits rather than relying on a single indicator (Bertolli et al., 2014; Pan et al., 2022). Thus, Chacón-Labella et al. (2023) have proposed a shift in focus toward the phenotypes of GI (which are the integrated expressions of all traits) instead of individual traits in isolation. This approach promises a more accurate expression of the complex trait-service relationships. Nevertheless, although a growing number of studies attempt to explore multivariate relationships among a cluster of functional traits through statistical methods (Rahman et al., 2020; Speak et al., 2020), it is essential to recognise that the arbitrary inclusion of variables can potentially lead to inadequate modelling (Chacón-Labella et al., 2023). Hence, further research could be tailored through selective and explorative statistical analyses to investigate the cause–effect relationships between traits and the relative functions (Bussotti and Pollastrini, 2015). On the other hand, the efficacy of functional traits is also affected by contextual factors. By synthesising 216 studies, Pan et al. (2022) found that about 20% of trait-service relationships were unstable, necessitating further elucidation in the context of geographic and climatic conditions. The interactions between functional traits and contextual factors are intricate, demanding additional research that also includes contextual variables (e.g. Fusaro et al., 2018), contributing to a more profound understanding of ecosystem processes.

4.2. Implications for GI planning and investment

Given the variable relationships between ESs and EDs, a more systematic approach that integrates biophysical and socioeconomic knowledge is required to manage trade-offs and synergies. In addition, the flow of ESs and EDs delivered by GI should be taken into account for the spatial and temporal implications from a planning and investment perspective.

Biophysically, ecosystem processes through which ESs and EDs are generated and interact with each other vary at different spatial scales. For example, shading, evapotranspiration, and enhanced convection are differentially important to microclimate regulation at the site, neighbourhood, and municipal scales (Gunawardena et al., 2017). Thus, functional traits corresponding to various scales of GI implementation are recommended, such as a denser canopy for shading (Helletsgruber et al., 2020), higher sap flow rates for evapotranspiration (Rahman et al., 2017), and greater surface roughness for convection efficiency (Gunawardena et al., 2017). In addition, socioeconomic contexts play a significant role in determining the scale of investment and the perception of value (Mell and Clement, 2020). Larger-scale GI developments often prioritise climate change mitigation and biodiversity conservation (Clement et al., 2015), potentially overlooking local socio-cultural values (Byrne et al., 2015). Consequently, effective tiering is suggested to address trade-offs and optimise GI outcomes across different scales (Mell and Clement, 2020).

Moreover, understanding the temporal dynamics of ESs and EDs delivery facilitates the optimisation of multifunctionality in the long term, balancing it with the short imperatives. For instance, Oldfield et al. (2015) indicated that biotic treatments hasten tree growth and enhance ESs delivery but also lead to higher mortality and loss of ES benefits in the long run. Viewing GI through a temporal lens highlights the importance of continuous monitoring and management practices (Mell and Clement, 2020). A case study in Illinois (Jessop et al., 2015) explicitly illustrated the shifting relationships from synergy to trade-offs between ESs after the development of wetlands without appropriate interventions. Other studies have examined the evolving values assigned to GI planning across various periods from a socio-cultural perspective (Lawrence, 1993). Given that the changes in societal value orientation may also alter the relationships between ESs and EDs, thus leading to intergenerational conflicts, the literature on adaptive management stresses the importance of continual adjustment based on feedback to improve decision-making (Tompkins and Adger, 2004).

Though the conventional evaluations of GI success focus primarily on the quantifiable biophysical impacts, this study emphasises the importance of integrating socioeconomic information in GI planning, in which trade-offs and synergies *per se* should be neutrally valued. Trade-offs tend to be portrayed as negative and synergies as positive in top-down approaches; however, this impression might be deceptive, given the divergent interests of stakeholders (Haase et al., 2012; Roman et al., 2021). Trade-offs and synergies only indicate the directional change of ecosystem processes, rather than the actual gains and losses. It has been widely reported that synergistic regulating ESs delivered by GI resulted in social EDs for certain groups of residents (Mell, 2022). Clement and Mell (2023) argue that future GI should be planned and realised through "co-production", "co-design", and "co-generation" with communities, where trade-offs and synergies can be informed by the perceptions of a wider range of stakeholders (e.g. planners, experts, and citizens). These co-concepts have been prioritised in European GI practices (Davies et al., 2021) and provided the promising prospect of confronting several issues, especially relating to diversity and inclusivity. Furthermore, community engagement makes trade-offs and synergies informed by the perceptions of all stakeholders, maximising the full potential of GI in the urban context (Hubacek and Kronenberg, 2013; Mell, 2022; Rall et al., 2019).

5. Conclusions and future research

The extensive integration of GI approaches in the planning and management of urban infrastructure reflects its contribution to human health and well-being. However, trade-offs and synergies between ESs and EDs should be understood explicitly to avoid unintended impacts on the environment and society. This review synthesised 96 GI case studies to reveal the research trends and gaps in this field. The results illustrate a growing literature of uneven geographic and climatological distribution, where the major studies concentrated on cities in the Global North with temperate oceanic or humid subtropical climates. Future research may shift the focus to the Global South with diverse climatic conditions, where the GI elements and demands for services may be different from the current mainstream regions. Additionally, this review identifies the flexibility of relationships between ESs and EDs, which are determined by neither the GI elements nor the mechanisms of association. Instead, there are three factors that cause trade-offs and synergies, namely characteristics of GI, contextual factors, and perception of stakeholders. Notwithstanding, the stakeholder dimension was not fully addressed in existing case studies and warrants further exploration.

The majority of studies reviewed relied heavily on the statistical correlation to identify trade-offs and synergies. The snapshot assessment of ESs and EDs only displays pattern-based relationships rather than causation. Functional traits provide the opportunity to understand the mechanistic process for trade-offs and synergies, but more research efforts should be paid to fill the knowledge gap on the trait-service relationship. Trade-offs and synergies *per se* should be 'value-free' in GI implementations, as they merely represent the dynamics of ESs and EDs and may be conceptualised differently by beneficiaries. Urban planning would benefit from a systemic integration of biophysical and socioeconomic knowledge with consideration of the spatial and temporal dynamics of ESs and EDs supply. Investment in and management of GI in an urban context should be based on a wise utilisation of trade-offs and synergies to balance short- and long-term benefits of GI, and to allocate these benefits appropriately to stakeholders.

Funding

This work was supported by the Australian National University and China Scholarship Council (ANU-CSC) scholarship [No. 202008510123].

CRediT authorship contribution statement

Andrew MacKenzie: Supervision, Validation, Writing – review & editing. **Baige Zhang:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to express our gratitude to Professor Peter Kanowski at the Australian National University for his valuable review and insightful suggestions on this work.

References

Abramowicz, D., Stępniewska, M., 2020. Public investment policy as a driver of changes in the ecosystem services delivery by an urban green infrastructure. Quaest. Geogr. 39, 5–18.
Ahern, J., 2016. Novel urban ecosystems: new nature (s) for the century of the city. Proc. Fábos Conf. Landsc. Greenway Plan. 5 (2), 60.
Albert, C., Von Haaren, C., 2017. Implications of applying the green infrastructure concept in landscape planning for ecosystem services in peri-urban areas: an expert survey and case study. Plan. Pract. Res. 32, 227–242.
Alves, A., Vojinovic, Z., Kapelan, Z., Sanchez, A., Gersonius, B., 2020. Exploring trade-offs among the multiple benefits of green-blue-grey infrastructure for urban flood mitigation. Sci. Total Environ. 703, 134980-134980.
Amorim, J.H., Engardt, M., Johansson, C., Ribeiro, I., Sannebro, M., 2021. Regulating and cultural ecosystem services of urban green infrastructure in the nordic countries: a systematic review. Int. J. Environ. Res. Public Health 18, 1–19.
Baik, J.-J., Kwak, K.-H., Park, S.-B., Ryu, Y.-H., 2012. Effects of building roof greening on air quality in street canyons. Atmos. Environ. 1994 (61), 48–55.
BenDor, T.K., Spurlock, D., Woodruff, S.C., Olander, L., 2017. A research agenda for ecosystem services in American environmental and land use planning. Cities 60, 260–271.
Benedict, M.A., McMahon, E.T., 2006. Green infrastructure: Linking landscapes and communities. Island Press, Washington, DC, USA.
Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404.
Bertolli, S.C., Mazzafera, P., Souza, G.M., 2014. Why is it so difficult to identify a single indicator of water stress in plants? A proposal for a multivariate analysis to assess emergent properties. Plant Biol. (Stuttg., Ger.) 16, 578–585.
Birkhofer, K., Diehl, E., Andersson, J., Ekroos, J., Früh-Müller, A., Machnikowski, F., Mader, V.L., Nilsson, L., Sasaki, K., Rundlöf, M., Wolters, V., Smith, H.G., 2015. Ecosystem services—current challenges and opportunities for ecological research. Front. Ecol. Evol. 2.
Brown, L.M., Anand, M., 2022. Plant functional traits as measures of ecosystem service provision. Ecosphere (Wash., D. C.) 13.
Brzoska, P., Spāģe, A., 2020. From city- to site-dimension: assessing the urban ecosystem services of different types of green infrastructure. Land (Basel) 9, 150.
Bussotti, F., Pollastrini, M., 2015. Evaluation of leaf features in forest trees: methods, techniques, obtainable information and limits. Ecol. Indic. 52, 219–230.
Byrne, J.A., Lo, A.Y., Yang, J.J., 2015. Residents' understanding of the role of green infrastructure for climate change adaptation in Hangzhou, China. Landsc. URBAN Plan 138, 132–143.
Cameron, R.W.F., Blanuša, T., 2016. Green infrastructure and ecosystem services – is the devil in the detail? Ann. Bot. 118, 377–391.
Cebrián-Piqueras, M.A., Trinogga, J., Trenkamp, A., Minden, V., Maier, M., Mantilla-Contreras, J., 2021. Digging into the roots: understanding direct and indirect drivers of ecosystem service trade-offs in coastal grasslands via plant functional traits. Environ. Monit. Assess. 193, 271-271.
Chacón-Labella, J., Hinojo-Hinojo, C., Bohner, T., Castorena, M., Violle, C., Vandvik, V., Enquist, B.J., 2023. How to improve scaling from traits to ecosystem processes. Trends Ecol. Evol. (Amst.) 38, 228–237.
Chang, H.-S., Lin, Z.-H., Hsu, Y.-Y., 2021. Planning for green infrastructure and mapping synergies and trade-offs: a case study in the Yanshuei River Basin. Taiwan. Urban For. Urban Green. 65, 127325.
Chatzimentor, A., Apostolopoulou, E., Mazaris, A.D., 2020. A review of green infrastructure research in Europe: challenges and opportunities. Landsc. Urban Plan. 198, 103775.
Cheng, X., Van Damme, S., Uyttenhove, P., 2021. A review of empirical studies of cultural ecosystem services in urban green infrastructure. J. Environ. Manag. 293, 112895-112895.
Cheshmehzangi, A., Butters, C., Xie, L., Dawodu, A., 2021. Green infrastructures for urban sustainability: Issues, implications, and solutions for underdeveloped areas. Urban For. Urban Green. 59, 127028.
Choi, C., Berry, P., Smith, A., 2021. The climate benefits, co-benefits, and trade-offs of green infrastructure: A systematic literature review. J. Environ. Manag. 291, 112583.
Cilliers, S., Cilliers, J., Lubbe, R., Siebert, S., 2013. Ecosystem services of urban green spaces in African countries—perspectives and challenges. Urban Ecosyst. 16, 681–702.

Clement, S., Mell, I.C., 2023. Nature, Democracy, and Sustainable Urban Transformations, Sustainability Transformations, Social Transitions and Environmental Accountabilities. Springer, pp. 79–120.
Clement, S., Moore, S.A., Lockwood, M., Mitchell, M., 2015. Using insights from pragmatism to develop reforms that strengthen institutional competence for conserving biodiversity. Policy Sci. 48, 463–489.
Conway, T.M., Yip, V., 2016. Assessing residents' reactions to urban forest disservices: A case study of a major storm event. Landsc. Urban Plan. 153, 1–10.
Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Ecol. Econ. 25, 3–15.
Crouzat, E., Mouchet, M., Turkelboom, F., Byczek, C., Meersmans, J., Berger, F., Verkerk, P.J., Lavorel, S., Diekötter, T., 2015. Assessing bundles of ecosystem services from regional to landscape scale: insights from the French Alps. J. Appl. Ecol. 52, 1145–1155.
Cruz, M.G., Sullivan, A.L., Gould, J.S., Sims, N.C., Bannister, A.J., Hollis, J.J., Hurley, R. J., 2012. Anatomy of a catastrophic wildfire: The Black Saturday Kilmore East fire in Victoria, Australia. For. Ecol. Manag. 284, 269–285.
Cuthbert, M.O., Rau, G.C., Ekström, M., O'Carroll, D.M., Bates, A.J., 2022. Global climate-driven trade-offs between the water retention and cooling benefits of urban greening. Nat. Commun. 13, 518-518.
Dallimer, M., Irvine, K.N., Skinner, A.M.J., Davies, Z.G., Rouquette, J.R., Maltby, L.L., Warren, P.H., Armsworth, P.R., Gaston, K.J., 2012. Biodiversity and the feel-good factor: understanding associations between self-reported human well-being and species richness. BioScience 62, 47–55.
Daniel, T.C., Muhar, A., Arnberger, A., Aznar, O., Boyd, J.W., Chan, K.M.A., Costanza, R., Elmqvist, T., Flint, C.G., Gobster, P.H., Grêt-Regamey, A., Lave, R., Muhar, S., Penker, M., Ribe, R.G., Schauppenlehner, T., Sikor, T., Soloviy, I., Spierenburg, M., Taczanowska, K., Tam, J., von der Dunk, A., 2012. Contributions of cultural services to the ecosystem services agenda. Proc. Natl. Acad. Sci. PNAS 109, 8812–8819.
Davies, C., Chen, W.Y., Sanesi, G., Lafortezza, R., 2021. The European Union roadmap for implementing nature-based solutions: A review. Environ. Sci. Policy 121, 49–67.
de Bello, F., Lavorel, S., Diaz, S., Harrington, R., Cornelissen, J.H.C., Bardgett, R.D., Berg, M.P., Cipriotti, P., Feld, C.K., Hering, D., Martins da Silva, P., Potts, S.G., Sandin, L., Sousa, J.P., Storkey, J., Wardle, D.A., Harrinson, P.A., Sveriges, l, 2010. Towards an assessment of multiple ecosystem processes and services via functional traits. Biodivers. Conserv. 19, 2873–2893.
Depietri, Y., 2022. Planning for urban green infrastructure: addressing tradeoffs and synergies. Current Opinion in Environmental. Sustainability 54, 101148.
Díaz, S., Purvis, A., Cornelissen, J.H.C., Mace, G.M., Donoghue, M.J., Ewers, R.M., Jordano, P., Pearse, W.D., 2013. Functional traits, the phylogeny of function, and ecosystem service vulnerability. Ecol. Evol. 3, 2958–2975.
Erlwein, S., Pauleit, S., 2021. Trade-offs between urban green space and densification: Balancing outdoor thermal comfort, mobility, and housing demand. Urban Plan. 6, 5–19.
Escobedo, F.J., Clerici, N., Staudhammer, C.L., Corzo, G.T., 2015. Socio-ecological dynamics and inequality in Bogota. Colomb. 'S. Public Urban For. Ecosyst. Serv. Urban For. Urban Green. 14, 1040–1053.
European Commission, 2013. Green Infrastructure (GI) – Enhancing Europe's Natural Capital. COM (2013) 249 Final.
Fiorani, F., Schurr, U., 2013. Future scenarios for plant phenotyping. Annu. Rev. Plant Biol. 64, 267–291.
Fitzky, A.C., Sandén, H., Karl, T., Fares, S., Calfapietra, C., Grote, R., Saunier, A., Rewald, B., 2019. The interplay between ozone and urban vegetation—BVOC emissions, ozone deposition, and tree ecophysiology. Front. For. Glob. Change 2.
Fuller, R.A., Irvine, K.N., Devine-Wright, P., Warren, P.H., Gaston, K.J., 2007. Psychological benefits of greenspace increase with biodiversity. Biol. Lett. 2005 (3), 390–394.
Fusaro, L., Mereu, S., Salvatori, E., Agliari, E., Fares, S., Manes, F., 2018. Modeling ozone uptake by urban and peri-urban forest: a case study in the Metropolitan City of Rome. Environ. Sci. Pollut. Res. Int. 25, 8190–8205.
Fusaro, L., Salvatori, E., Mereu, S., Marando, F., Scassellati, E., Abbate, G., Manes, F., 2015. Urban and peri-urban forests in the metropolitan area of Rome: ecophysiological response of Quercus ilex L. in two green infrastructures in an ecosystem services perspective. Urban For. Urban Green. 14, 1147–1156.
Grard, B.J.P., Chenu, C., Manouchehri, N., Houot, S., Frascaria-Lacoste, N., Aubry, C., 2018. Rooftop farming on urban waste provides many ecosystem services. Agron. Sustain. Dev. 38.
Grime, J.P., 1998. Benefits of plant diversity to ecosystems: immediate, filter and founder effects. J. Ecol. 86, 902–910.
Gunawardena, K.R., Wells, M.J., Kershaw, T., 2017. Utilising green and bluespace to mitigate urban heat island intensity. Sci. Total Environ. 584-585, 1040–1055.
Haase, D., 2015. Reflections about blue ecosystem services in cities. Sustain. Water Qual. Ecol. 5, 77–83.
Haase, D., Schwarz, N., Strohbach, M., Kroll, F., Seppelt, R., 2012. Synergies, trade-offs, and losses of ecosystem services in urban regions: an integrated multiscale framework applied to the Leipzig-Halle Region, Germany. Ecol. Soc. 17, 22-22.
Haines-Young, R., Potschin, M., 2018. Common International Classification of Ecosystem Services V 5.1—Guidance on the Application of the Revised Structure, Nottingham, UK.
Hanisch, M., Schweiger, O., Cord, A.F., Volk, M., Knapp, S., Wainwright, C., 2020. Plant functional traits shape multiple ecosystem services, their trade-offs and synergies in grasslands. J. Appl. Ecol. 57, 1535–1550.
Hansen, R., Olafsson, A.S., van der Jagt, A.P.N., Rall, E., Pauleit, S., 2019. Planning multifunctional green infrastructure for compact cities: What is the state of practice? Ecol. Indic. 96, 99–110.
Hansen, R., Pauleit, S., 2014. From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for urban areas. Ambio 43, 516–529.
Helletsgruber, C., Gillner, S., Gulyas, A., Junker, R.R., Tanacs, E., Hof, A., 2020. Identifying Tree Traits for Cooling Urban Heat Islands-A Cross-City Empirical Analysis. Forests 11, 1064.
Hossu, C.A., Iojă, I.-C., Onose, D.A., Niță, M.R., Popa, A.-M., Talabă, O., Inostroza, L., 2019. Ecosystem services appreciation of urban lakes in Romania. Synerg. Trade-offs Mult. users. Ecosyst. Serv. 37, 100937.
Howe, C., Suich, H., Vira, B., Mace, G.M., 2014. Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. Glob. Environ. Change 28, 263–275.
Hubacek, K., Kronenberg, J., 2013. Synthesizing different perspectives on the value of urban ecosystem services. Landsc. Urban Plan. 109, 1–6.
Jessop, J., Spyreas, G., Pociask, G.E., Benson, T.J., Ward, M.P., Kent, A.D., Matthews, J. W., 2015. Tradeoffs among ecosystem services in restored wetlands. Biol. Conserv. 191, 341–348.
Kirkpatrick, J.B., Davison, A., Daniels, G.D., 2012. Resident attitudes towards trees influence the planting and removal of different types of trees in eastern Australian cities. Landsc. Urban Plan. 107, 147–158.
Kirkpatrick, J.B., Davison, A., Harwood, A., 2013. How tree professionals perceive trees and conflicts about trees in Australia's urban forest. Landsc. Urban Plan. 119, 124–130.
Kong, L., Shi, Z., Chu, L.M., 2014. Carbon emission and sequestration of urban turfgrass systems in Hong Kong. The. Sci. Total Environ. 473-474, 132–138.
Kronenberg, J., Andersson, E., Barton, D.N., Borgström, S.T., Langemeyer, J., Björklund, T., Haase, D., Kennedy, C., Koprowska, K., Łaszkiewicz, E., McPhearson, T., Stange, E.E., Wolff, M., 2021. The thorny path toward greening: unintended consequences, trade-offs, and constraints in green and blue infrastructure planning, implementation, and management. Ecol. Soc. 26, 1.
Lanta, V., Klimešová, J., Martincová, K., Janeček, Š., Doležal, J., Rosenthal, J., Lepš, J., Klimeš, L., 2011. A test of the explanatory power of plant functional traits on the individual and population levels. Perspect. Plant Ecol., Evol. Syst. 13, 189–199.
Lavorel, S., Grigulis, K., Lamarque, P., Colace, M.P., Garden, D., Girel, J., Pellet, G., Douzet, R., 2011. Using plant functional traits to understand the landscape distribution of multiple ecosystem services. J. Ecol. 99, 135–147.
Lawrence, H.W., 1993. The neoclassical origins of modern urban forests. For. Conserv. Hist. 37, 26–36.
Lin, B.B., Meyers, J.A., Barnett, G.B., 2019. Establishing Priorities for Urban Green Infrastructure Research in Australia. Urban Policy Res. 37, 30–44.
Loughner, C.P., Allen, D.J., Zhang, D.-L., Pickering, K.E., Dickerson, R.R., Landry, L., 2012. Roles of Urban Tree Canopy and Buildings in Urban Heat Island Effects: Parameterization and Preliminary Results. J. Appl. Meteorol. Climatol. 51, 1775–1793.
Lyytimäki, J., Sipilä, M., 2009. Hopping on one leg – the challenge of ecosystem disservices for urban green management. Urban For. Urban Green. 8, 309–315.
Mason, N.W.H., Mouillot, D., Lee, W.G., Wilson, J.B., 2005. Functional richness, functional evenness and functional divergence: the primary components of functional diversity. Oikos 111, 112–118.
McShane, T.O., Hirsch, P.D., Trung, T.C., Songorwa, A.N., Kinzig, A., Monteferri, B., Mutekanga, D., Thang, H.V., Dammert, J.L., Pulgar-Vidal, M., Welch-Devine, M., Peter Brosius, J., Coppolillo, P., O'Connor, S., 2011. Hard choices: Making trade-offs between biodiversity conservation and human well-being. Biol. Conserv. 144, 966–972.
MEA, 2005. Ecosystems and human well-being: Desertification Synthesis. Island Press, Washington, DC.
Meerow, S., 2020. The politics of multifunctional green infrastructure planning in New York City. Cities 100, 102621.
Meerow, S., Newell, J.P., 2017. Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit. Landsc. Urban Plan. 159, 62–75.
Mell, I., 2022. Examining the Role of Green Infrastructure as an Advocate for Regeneration. Front. Sustain. Cities 4.
Mell, I., Clement, S., 2020. Progressing Green Infrastructure planning: understanding its scalar, temporal, geo-spatial and disciplinary evolution. Impact Assess. Proj. Apprais. 38, 449–463.
Mell, I.C., 2013. Can you tell a green field from a cold steel rail? Examining the "green" of Green Infrastructure development. Local Environ. 18, 152–166.
Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Reprint—Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. Phys. Ther. 89, 873–880.
Mouchet, M.A., Lamarque, P., Martín-López, B., Crouzat, E., Gos, P., Byczek, C., Lavorel, S., 2014. An interdisciplinary methodological guide for quantifying associations between ecosystem services. Glob. Environ. Change 28, 298–308.
Mouton, J., Babbie, E., 2001. The Practice of Social Research. Wadsworth Publishing Company, Cape Town.
Naumann, S., McKenna, D., Kaphengst, T., Pieterse, M., Rayment, M., 2011. Design, Implementation and Cost Elements of Green Infrastructure Projects. Ecologic Institute and GHK Consulting, Overland Park, KS, USA.
Ndong, G.O., Therond, O., Cousin, I., 2020. Analysis of relationships between ecosystem services: a generic classification and review of the literature. Ecosyst. Serv. 43, 101120.
Nowak, D.J., Crane, D.E., 2002. Carbon storage and sequestration by urban trees in the USA. Environ. Pollut. 1987 (116), 381–389.

O'Brien, A.M., Mc Guckin, C., 2016. The Systematic Literature Review Method: Trials and Tribulations of Electronic Database Searching at Doctoral Level. SAGE Publications, London, UK.
Ode Sang, Å., Knez, I., Gunnarsson, B., Hedblom, M., Naturvetenskapliga, F., Faculty of, S., Department of, B., Environmental, S., Göteborgs, U., Institutionen för biologi och, M., Gothenburg, U., Mistra Urban, F., Sveriges, l, 2016. The effects of naturalness, gender, and age on how urban green space is perceived and used. Urban For. Urban Green. 18, 268–276.
Oldfield, E.E., Felson, A.J., Auyeung, D.S.N., Crowther, T.W., Sonti, N.F., Harada, Y., Maynard, D.S., Sokol, N.W., Ashton, M.S., Warren, R.J., Hallett, R.A., Bradford, M. A., 2015. Growing the urban forest: tree performance in response to biotic and abiotic land management. Restor. Ecol. 23, 707–718.
Pan, Q., Wen, Z., Wu, T., Zheng, T., Yang, Y., Li, R., Zheng, H., 2022. Trade-offs and synergies of forest ecosystem services from the perspective of plant functional traits: A systematic review. Ecosyst. Serv. 58, 101484.
Parker, J., de Baro, M.E.Z., 2019. Green infrastructure in the urban environment: a systematic quantitative review. Sustain. (Basel, Switz.) 11, 3182.
Pickering, C., Byrne, J., 2014. The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. High. Educ. Res. Dev. 33, 534–548.
Plas, Vd.F., Schröder-Georgi, T., Weigelt, A., Barry, K., Meyer, S., Alzate, A., Barnard, R. L., Buchmann, N., Kroon, dH., Ebeling, A., Eisenhauer, N., Engels, C., Fischer, M., Gleixner, G., Hildebrandt, A., Koller-France, E., Leimer, S., Milcu, A., Mommer, L., Niklaus, P.A., Oelmann, Y., Roscher, C., Scherber, C., Scherer-Lorenzen, M., Scheu, S., Schmid, B., Schulze, E.D., Temperton, V., Tscharntke, T., Voigt, W., Weisser, W., Wilcke, W., Wirth, C., 2020. Plant traits alone are poor predictors of ecosystem properties and long-term ecosystem functioning. Nat. Ecol. Evol. 4, 1602–1611.
Plieninger, T., Dijks, S., Oteros-Rozas, E., Bieling, C., 2013. Assessing, mapping, and quantifying cultural ecosystem services at community level. Land Use Policy 33, 118–129.
Rahman, M.A., Moser, A., Rötzer, T., Pauleit, S., 2017. Within canopy temperature differences and cooling ability of Tilia cordata trees grown in urban conditions. Build. Environ. 114, 118–128.
Rahman, M.A., Stratopoulos, L.M.F., Moser-Reischl, A., Zölch, T., Häberle, K.-H., Rötzer, T., Pretzsch, H., Pauleit, S., 2020. Traits of trees for cooling urban heat islands: a meta-analysis. Build. Environ. 170, 106606.
Rall, E., Hansen, R., Pauleit, S., 2019. The added value of public participation GIS (PPGIS) for urban green infrastructure planning. Urban For. Urban Green. 40, 264–274.
Raudsepp-Hearne, C., Peterson, G.D., Bennett, E.M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc. Natl. Acad. Sci. - PNAS 107, 5242–5247.
Reed, S.E., Merenlender, A.M., 2008. Quiet, Nonconsumptive recreation reduces protected area effectiveness: quiet recreation in protected areas. Conserv. Lett. 1, 146–154.
Riechers, M., Noack, E.M., Tscharntke, T., 2017. Experts' versus laypersons' perception of urban cultural ecosystem services. Urban Ecosyst. 20, 715–727.
Rodríguez, J.P., Beard, J.T.D., Bennett, E.M., Cumming, G.S., Cork, S.J., Agard, J., Dobson, A.P., Peterson, G.D., 2006. Trade-offs across space, time, and ecosystem services. Ecol. Soc. 11, 28.
Roman, L.A., Conway, T.M., Eisenman, T.S., Koeser, A.K., Ordóñez Barona, C., Locke, D. H., Jenerette, G.D., Östberg, J., Vogt, J., 2021. Beyond 'trees are good': disservices, management costs, and tradeoffs in urban forestry. Ambio 50, 615–630.
Russo, A., Cirella, G.T., 2019. Edible urbanism 5.0. Palgrave Communications 5.
Samuelson, P.A., 1970. Economics. McGraw-Hill Book Company.
Säumel, I., Reddy, S., Wachtel, T., 2019. Edible City Solutions—One Step Further to Foster Social Resilience through Enhanced Socio-Cultural Ecosystem Services in Cities. Sustain. (Basel, Switz.) 11, 972.
Smith, A.C., Harrison, P.A., Pérez Soba, M., Archaux, F., Blicharska, M., Egoh, B.N., Erős, T., Fabrega Domenech, N., György, Á.I., Haines-Young, R., Li, S., Lommelen, E., Meiresonne, L., Miguel Ayala, L., Mononen, L., Simpson, G., Stange, E., Turkelboom, F., Uiterwijk, M., Veerkamp, C.J., Wyllie de Echeverria, V., Sveriges, l, 2017. How natural capital delivers ecosystem services: a typology derived from a systematic review. Ecosyst. Serv. 26, 111–126.
Spake, R., Lasseur, R., Crouzat, E., Bullock, J.M., Lavorel, S., Parks, K.E., Schaafsma, M., Bennett, E.M., Maes, J., Mulligan, M., Mouchet, M., Peterson, G.D., Schulp, C.J.E., Thuiller, W., Turner, M.G., Verburg, P.H., Eigenbrod, F., 2017. Unpacking ecosystem service bundles: Towards predictive mapping of synergies and trade-offs between ecosystem services. Glob. Environ. Change 47, 37–50.
Speak, A., Montagnani, L., Wellstein, C., Zerbe, S., 2020. The influence of tree traits on urban ground surface shade cooling. Landsc. Urban Plan. 197, 103748.
Suppakittpaisarn, P., Larsen, L., Sullivan, W.C., 2019. Preferences for green infrastructure and green stormwater infrastructure in urban landscapes: Differences between designers and laypeople. Urban For. Urban Green. 43, 126378.
Sussams, L.W., Sheate, W.R., Eales, R.P., 2015. Green infrastructure as a climate change adaptation policy intervention: Muddying the waters or clearing a path to a more secure future? J. Environ. Manag. 147, 184–193.
Tompkins, E.L., Adger, W.N., 2004. Does Adaptive Management of Natural Resources Enhance Resilience to Climate Change? Ecol. Soc. 9, 10-10.
Tran, T.J., Helmus, M.R., Behm, J.E., 2020. Green infrastructure space and traits (GIST) model: Integrating green infrastructure spatial placement and plant traits to maximize multifunctionality. Urban For. Urban Green. 49, 126635.
Tuhkanen, H., Boyland, M., Han, G., Patel, A., Johnson, K., Rosemarin, A., Lim Mangada, L., 2018. A Typology Framework for Trade-Offs in Development and Disaster Risk Reduction: A Case Study of Typhoon Haiyan Recovery in Tacloban, Philippines. Sustain. (Basel, Switz.) 10, 1924.
Violle, C., Navas, M.-L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I., Garnier, E., 2007. Let the Concept of Trait Be Functional. Oikos 116, 882–892.
von Döhren, P., Haase, D., 2015. Ecosystem disservices research: A review of the state of the art with a focus on cities. Ecol. Indic. 52, 490–497.
Walker, R.H., 2021. Engineering gentrification: urban redevelopment, sustainability policy, and green stormwater infrastructure in Minneapolis. J. Environ. Policy Plan. 23, 646–664.
Well, F., Ludwig, F., 2021. Development of an integrated design strategy for blue-green architecture. Sustain. (Switz.) 13, 7944.
Wright, H., 2011. Understanding green infrastructure: the development of a contested concept in England. Local Environ. 16, 1003–1019.