

Valuing Ecosystem Services in Cost-Benefit Analyses of Stormwater Management and Urban Heat Island Adaptation

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Dedication

To my parents for instilling in me an unquenching thirst for knowledge, to my loving wife of many years for her continuous love and support, and to my German family for making Germany feel like home.

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List of abbreviations

BCR	Benefit-Cost Ratio
CBA	Cost-benefit analysis
EU	European Union
MEA	Millennium Ecosystem Assessment
NPV	Net Present Value
SUDS	Sustainable Urban Drainage Systems
TEEB	The Economics of Ecosystems and Biodiversity

1. Introduction

With the majority of people in the world living in cities and projections showing an expected 68% of the population to be living in urban areas by 2050 (UN DESA, 2018), urbanization currently, and even more so in the future, represents numerous challenges for cities. By means of economies of scale, it has been argued that urban areas can fulfill basic human needs with lower costs (Bettencourt et al., 2007). However, experimental evidence indicates the adverse effects of urbanization on human health (e.g., Lederbogen et al., 2011). Moreover, urbanization brings together a host of socio-ecological issues as these areas account for high proportions of greenhouse gas emissions, energy consumption and resource use (Poumanyong and Kaneko, 2010) as well as high rates of land-use change, biodiversity loss and altered biogeochemical and hydrological systems (Grimm et al., 2008).

Although the number of challenges may be daunting, some optimism may be found in addressing the challenges as opportunities for developing sustainable cities that restore urban ecosystems (Elmqvist et al., 2015). Green infrastructure—a network of decentralized measures, such as green roofs, trees, and façade greening, that supports natural ecological processes (Benedict and McMahon, 2006)—embodies sustainability and addresses a multitude of urban challenges simultaneously (Hansen and Pauleit, 2014). Urban green infrastructure supports not only the ecological health and wellbeing of cities but can also improve the quality of life urban residents by providing for a number of ecosystem services (Venkataramanan et al., 2019). Ecosystem services are the benefits that humans obtain from ecosystems, and several of these services are enjoyed in the urban environment, termed urban ecosystem services (Bolund and Hunhammer, 1999). For example, green roofs, trees and façade greening not only contribute to stormwater management but also help to mitigate the urban heat island effect, improve urban biodiversity, sequester carbon dioxide, reduce air pollution and provide for a number of other services (Demuzere et al., 2014).

Although the literature on ecosystem services is rich and the concept has taken root in the political sphere in many countries (Hansen et al., 2015), it is not always clear how to use the information in decision making, especially concerning economic valuation (Laurans et al., 2013). The economic valuation of environmental impacts in cost-benefit analyses (CBAs) is generally considered to be a method of improving transparency and

efficiency in decision making (Jürgen Meyerhoff and Dehnhardt, 2009), and the economic valuation of ecosystem services is promoted as a means to reverse the declining rates of provision of the services (NRC, 2005). Several studies have already performed economic valuations of green infrastructure but have only evaluated the economic feasibility of single measures, such as green roofs (Bianchini and Hewage, 2012; Nurmi et al., 2016, 2013), façade greening (Perini and Rosasco, 2013) or green spaces (Zhang et al., 2012), or only valued single benefits, such as the influence on housing prices of green space (Wüstemann and Kolbe, 2017). Moreover, many economic analyses have directly evaluated the costs of benefits of green infrastructure for stormwater management but lack an economic valuation of the multiple additional ecosystem services provided (Joksimovic and Alam, 2014; Liu et al., 2014; Montalto et al., 2007; Spatari et al., 2011; Zhang et al., 2013). Especially the economic valuation of positive impacts on human health of heat regulation services of green infrastructure remains a hitherto gap in the literature. Few studies have estimated reductions in heat-related mortality with the implementation of green infrastructure (e.g., Chen et al., 2014; Dang et al., 2018; Stone et al., 2014), and no studies have performed economic valuations of such scenarios of implementation while simultaneously addressing the multitude of additional ecosystem services.

Although these studies enrich the literature on the value of green infrastructure to urban societies, there is a lack of research at the spatial scale of analysis used in urban planning, and the scale of analysis can play an important role in the management of multi-functional spaces and the attainment of goals in ecosystem services (Andersson et al., 2015). Larondelle and Lauf (2016) developed a methodology for estimating the demand and supply of ecosystem services at the neighborhood level, which is applicable for actual urban planning frameworks, and demonstrated high demands for ecosystem services such as urban heat regulation and pollutant removal across many areas of Berlin, Germany. Given that neighborhood-level analyses are underrepresented in the literature (Haase et al., 2014), there remain research gaps in addressing the demands for ecosystem services on the scale of the neighborhood.

Given these gaps in the literature, this dissertation aims to improve the methodology and analyze the economic feasibility of green infrastructure by integrating the economic valuation of ecosystem services. The first and third manuscripts analyze scenarios of implementation for stormwater management at the neighborhood scale and

valuing the ecosystem services accordingly. The second and third manuscripts both aim to fill the research gap associated with economic valuations of health-related impacts of the urban heat mitigation of green infrastructure. Furthermore, the second manuscript builds on the methodology developed in the first manuscript by improving on the sensitivity analysis to obtain an improved portrayal of the economic risk and uncertainty, whereas the third manuscript furthermore incorporates recent advancements in the discounting of ecosystem services.

2. Background and concepts

2.1. Ecosystem services

As the benefits that humans obtain through ecosystems, ecosystem services play vital roles in supporting the health and wellbeing of societies, especially in urban contexts (Bolund and Hunhammer, 1999). Although ecosystem services are critical for sustaining human populations and the demand for ecosystem services can be high in urban areas (e.g., Larondelle and Lauf, 2016), large multi-regional, interdisciplinary studies such as the Millennium Ecosystem Assessment have demonstrated significant declining trends in services across the world due to unprecedented rates of ecosystem alteration (MA and Millennium Ecosystem Assessment, 2005).

In order to prevent further degradation of ecosystem, several frameworks have been proposed to identify such ecosystem services. With the help of classification systems, the various ecosystem service frameworks accrue numerous benefits ranging from knowledge transfer and management to unifying language and understanding of the complex interactions (Finisdore et al., 2020). By being able to identify and understand such services, the global initiatives describe the means to measure and value such contributions of nature to society. As a foundational framework, ecosystem services have been classified according to supporting, provisioning, regulating and cultural services within the Millennium Ecosystem Assessment (MEA) (MA and Millennium Ecosystem Assessment, 2005). This global initiative set out to account for the numerous benefits that humans obtain from ecosystems by conceptualizing the interactions between humans, ecosystems, the services themselves and the causes of change. As a further framework that extends the MEA, The Economics of Ecosystem Services and Biodiversity (TEEB) framework perpetuated the classification while additionally proposing a base

methodology for the monetary valuations of the ecosystem services (TEEB, 2010). This framework has been adopted as the basis for the evaluation of ecosystem services in the three manuscripts of this dissertation, and a conceptualization of such services indicated in the framework is found in Table 1. This methodology has been especially adapted for use in urban contexts (TEEB – The Economics of Ecosystems and Biodiversity, 2011). Arising out of needs for increased precision and improved analytical methods (Costanza et al., 2017), several further classifications have been proposed in recent years, such as the Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2018), the Final Ecosystem Services Classification System (Landers and Nahlik, 2013), the National Ecosystem Services Classification System (EPA, 2015), and the classification according to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Díaz et al., 2015), which propose similar categories as those found in the previous frameworks but attempt a more comprehensive analysis of services at different levels. Although these frameworks are important especially for considering ecosystem services accruing at various spatial scales, the frameworks according to TEEB and MEA both suffice for the analyses in the manuscripts of this dissertation as only the urban context is explored.

Table 1. Ecosystem service categorization of the TEEB framework (TEEB – The Economics of Ecosystems and Biodiversity, 2011).

Category	Description	Ecosystem services
Provisioning	Services that pertain to the production of materials or energy through ecosystems	Food production Raw materials Fresh water Medicinal resources
Regulating	Services in which ecosystems directly regulate air and soil quality or provide for the controlling of floods and diseases	Local climate and air quality regulation Carbon sequestration and storage Moderation of extreme events Wastewater treatment Erosion prevention and maintenance of soil fertility Pollination Biological control
Supporting	Services that support the functioning of other ecosystem services and provide habitats for organisms.	Habitats for species Maintenance of genetic diversity Recreation and mental and physical health
Cultural	Further benefits that humans obtain through contact with ecosystems in a non-material nature and support health and wellbeing.	Tourism Aesthetic appreciation and inspiration for culture, art and design Spiritual experience and sense of place

In recent years, a growing interest in the provision of urban ecosystem services has taken root (Haase et al., 2014). Numerous studies have proposed the use of the urban ecosystem services concept in planning for sustainable and resilient cities (Jansson, 2013; McPhearson et al., 2015; Wolch et al., 2014). Although urban areas offer residents

benefits in terms of economies of scale and lower costs for fulfilling basic needs (Bettencourt et al., 2007), urban areas bring together various environmental and human health issues such as land-use change and biodiversity, climate change, and altered biogeochemical and hydrological systems (Grimm et al., 2008). For these reasons, it is of paramount interest to understand the social-ecological systems and their drivers of change and to reconnect urban areas to the biosphere (Andersson et al., 2014).

Particularly important in identifying and valuing urban ecosystem services is the spatial application. Spatially explicit elicitation of urban ecosystem services and the valuation thereof can inform urban planning and policies, but a lack of this orientation in the literature was present until recent years (Haase et al., 2014). Recent studies have demonstrated the application of spatially modeling the demand and supply of ecosystem services in urban areas (e.g., Larondelle and Lauf, 2016). By taking a fine scale approach, cities are able to analyze the benefits accruing to society of the efforts in investing in measures that produce urban ecosystem services. This remains an important consideration for urban planners and policymakers who make decisions on district or neighborhood levels.

Although the number of studies on urban ecosystem services has risen, several extensive challenges remain to be conquered ranging from the spatial coverage of the assessments to the transferability of data and inclusion of results in actual urban planning (Luederitz et al., 2015). The three manuscripts in this dissertation address the issues of data transferability, spatial coverage and the potential for inclusion of the results in actual urban planning. While the first manuscript uses scenarios produced by local stakeholders given a set of urban goals to be achieved (i.e., stormwater management, urban heat, biodiversity, etc.), it also provides a framework for estimating and valuing the urban ecosystem services generated through sustainable stormwater management scenarios. This framework is used in the second and third manuscript and furthermore extended upon to include the urban heat mitigation services of green infrastructure.

2.2. Green infrastructure

While green infrastructure refers to the broad strategies in planning, both in urban and wider contexts, that strive for the implementation of measures resembling nature (Fletcher et al., 2015), it also refers to the network of decentralized measures supporting natural ecological processing (Benedict and McMahon, 2006). The decentralized

measures of green infrastructure range from green spaces and corridors to building level measures such as green roofs, trees, swales, or permeable pavement (Fletcher et al., 2015). In urban contexts, green infrastructure is especially important for addressing urban issues such as stormwater management (Li and Bergen, 2017), urban heat islands (Bartesaghi Koc et al., 2018), energy consumption (Besir and Cuce, 2018), human health (van den Berg et al., 2015), and air pollution (Rowe, 2011).

Whereas green infrastructure encompasses broader strategies for addressing various policy goals, sustainable urban drainage systems (SUDS) include many of the same specific measures but ultimately aim to address urban stormwater issues. SUDS support the natural detention, evaporation and infiltration of stormwater as opposed to conventional methods in which stormwater is either conveyed to wastewater treatment plants or directly to nearby water bodies. Such conventional methods lead to combined sewer overflows, which leads to heavy deterioration of the quality of receiving water bodies and to high rates of fish mortality (Riechel et al., 2016). In other conventional systems where stormwater runoff is conveyed separately from sewer systems, dust and heavy metals from impervious surfaces are directly deposited into receiving water bodies (Wicke et al., 2015). Furthermore, the flow regimes in these water bodies may also be affected (Niezgoda and Johnson, 2005). By slowing the conveyance of stormwater to the water bodies through natural detention, by allowing for increased evaporation and by improving natural infiltration, SUDS provide for the sustainable management of stormwater.

Although SUDS consist of measures such as rainwater harvesting, permeable pavement, swales and trenches, many of the specific measures in SUDS are also found within strategies implementing green infrastructure. Green roofs, façade greening and urban trees are all measures found within both planning approaches and compose the common set of measures found in the three manuscripts of this dissertation. The first manuscript analyses full SUDS scenarios, whereas manuscript two investigates scenarios with the subset of SUDS measures that can be subsumed under green infrastructure, including trees, green roofs and low vegetation. The third manuscript also focuses on a subset of SUDS measures, namely, green roofs, façade greening and trees, in order to estimate the impact of such measures in reducing the urban heat island effect.

SUDS, and more inclusively, green infrastructure, provide numerous additional urban ecosystem services alongside stormwater runoff reduction (Prudencio and Null, 2018; Scholz et al., 2013). These ecosystem services are essential given high rates of land use change, and green infrastructure is posed as one solution to reverse the alarming rates of the loss of ecosystem services (Maes et al., 2015). Green roofs and façade greening alone provide the bulk of additional ecosystem services including energy savings, reduction of the urban heat island effect, stormwater management, aesthetic improvements, carbon sequestration, air pollution mitigation, and biodiversity improvements (Besir and Cuce, 2018) as well as the supporting of the protection of building surfaces from weathering (Kosareo and Ries, 2007; Wong et al., 2010). Therefore, green infrastructure measures are seen as multifunctional elements that can address multiple urban issues simultaneously (Hansen and Pauleit, 2014).

Given implications of multifunctionality, scale plays an important role in the assessment of green infrastructure (Demuzere et al., 2014). Although single measures, such as green roofs, provide numerous benefits on their own (Clark et al., 2008), scaling the implementation of single measures can provide additional benefits such as the reduced necessary capacity of stormwater infrastructure and the associated operational costs (Niu et al., 2010). Moreover, single green infrastructure measures may help to reduce extreme heat directly at or near surface (Köhler and Kaiser, 2019), which can reduce cooling needs (von Tils, 2017), but the benefits to society in terms of urban heat mitigation may only result after a wider scale application of such measures (Santamouris, 2014). Such considerations increase the importance of analyzing scenarios of implementation on the neighborhood level, and by extending the analyses to whole districts, critical implications for urban planning can be drawn, especially in the context of sustainable stormwater management (Riechel et al., 2020) or urban heat island adaptation (Li et al., 2014).

2.3. Cost-benefit analysis

CBA is a method of providing economic grounds of project or policy approval. The decision is based on the weighing of costs and benefits of such an intervention over a given period of time in a calculation as a single number. A social CBA supports decision-making processes by estimating the attributable welfare changes to society, whereas a financial CBA considers the estimable cash inflows and outflows of an intervention (European Commission, 2014). For social CBAs, the intervention is

approved if a net benefit to society is achieved, ensuring a total improvement in societal welfare. In contrast to a financial analysis, a social CBA includes the costs and benefits to society, mostly with no direct monetary exchange due to a lack of an available market. For such costs and benefits, methods are employed to estimate the value thereof. The valuation process follows the Total Economic Value framework, for which distinct methods are used to estimate use and non-use values (European Commission, 2014).

Several European Union (EU) directives deem the use of CBA as necessary for considering approval of projects and policy proposals such as the Marine Strategy Framework Directive (Commission, 2008) and the Energy Efficiency Directive (European Commission, 2012). Policy makers working under the Water Framework Directive in the EU are also encouraged to use economic analyses as decision tools in planning for water basin management (European Commission, 2000). By incorporating such economic analyses into the planning of policies and projects, transparency can be achieved in policy making (J. Meyerhoff and Dehnhardt, 2009).

CBA provides a method of deciding between multiple projects or policies based on a small set of indices using discounting to take into account costs and benefits over time. Common indices include the Net Present Value (NPV) and the Benefit-Cost Ratio (BCR), which are both used for the analyses in the manuscripts of this dissertation. The NPV subtracts the discounted costs from the discounted benefits, whereas the BCR divides the discounted benefits by the discounted costs (European Commission, 2014). In the event that the calculated NPV remains positive or the BCR above 1, the project or policy is assumed to have economic grounds for approval.

Discounting refers to the comparison of value or wellbeing in today's terms versus some future time. The choice of the discount scheme remains a critical topic across research domains, especially within climate change economics where the discount rate can lead to starkly contrasting policy recommendations (Hampicke, 2011). While financial CBAs rely on financial discount rates that resemble market interest rates (i.e., the opportunity cost of capital), social CBAs utilize social discount rates that may reflect society's rate of return on private investments or society's rate of time preference (European Commission, 2014). Basing the social discount rate on the rate of time preference, the Ramsey model of discounting is typically employed, which includes the pure rate of time preference, the elasticity of the marginal utility of consumption and the

expected growth rate of per capita consumption (Zhuang et al., 2007). The standard approach to discounting costs and benefits in CBAs is to adopt a constant rate in exponential discounting, but evidence suggests that society's preferences do not always follow this scheme (Frederick et al., 2002). For example, hyperbolic discount schemes (i.e., a declining discount rate over time) may more closely represent preferences concerning the impacts of long-term policies (Gowdy et al., 2013), such as is the case with climate change (Karp, 2005).

Several other concerns over discounting have been made apparent for carrying out CBAs of projects and policies relating to environmental problems. Given the fact that ethical issues arise out of exponential discounting schemes resulting in virtually irrelevant effects in the long term (Dasgupta, 2008), different goods and services may require separate discount rates (Hasselman et al., 1997; Tol, 2004). Generally, there is a difference between environmental goods or services and manufactured goods, and the former should be discounted at a lower rate than the latter (Weikard and Zhu, 2005). Given that the rate of provision of many ecosystem services are in decline, Baumgärtner et al. (2015) demonstrated through a Ramsey model of discounting that ecosystem services should be discounted up to 2.1% lower than manufactured goods, depending on the level of development of the country. This conclusion relies on the fact that the marginal utility of consumption and the growth rate differ between ecosystem services and manufactured goods. This has been further extended by Drupp (2018), who compared the limits of substitution between manufactured goods and ecosystem services and further supported the dual discounting scheme of ecosystem services with lower rates than for manufactured goods. Zhu et al. (2019) took a similar approach by addressing the scarcity of ecosystem services and concluding that if ecosystem services cannot easily be substituted in production, and consequently consumption, the discount rate converges to a low value. Given these recent advances and uptake of the concept (e.g., Vasquez-Lavín et al., 2019) in the research on discounting of ecosystem services, the third manuscript replaces the conventional single discount rate for the dual discounting scheme for valuing the future provision of ecosystem services of green infrastructure.

2.4. Ecosystem service valuation

Ecosystem services provide significant value to humans, and these values are often considered social values for which no market exists, leading to no direct monetary

exchanges. For this reason, the total economic value framework is employed to assess the changes in wellbeing of humans as a result in the change in environmental quality through the provision of ecosystem services (European Commission, 2014). This framework is composed of the assessment methods for use values and non-use values (Figure 1). Use values pertain to the social benefits gained by the direct use of the good or service in question (i.e., direct use value), by the provision of secondary goods and services (i.e., indirect use value) and by the potential future use of the good (i.e., option value). Non-use values comprise the values generated by the pure existence of goods and services without actual consumption (i.e., existence value) and the values attached to preserving goods and services for others or for future generations (i.e., bequest or altruistic values, respectively). The set of methods include both the estimation of revealed preferences, for example, through the travel cost method, hedonic pricing method or market price method, and the elicitation of stated preferences, for example, through contingent valuation or choice models (Pearce et al., 2006). The strength in revealed preference methods relies on the estimation of values through observational evidence and are therefore less prone to various errors resulting from biases in stated preference methods (Champ et al., 2017). However, revealed preferences also only elicit the direct use values, which excludes the elicitation of non-use values. Generally, stated preference methods can capture both use and non-use values.

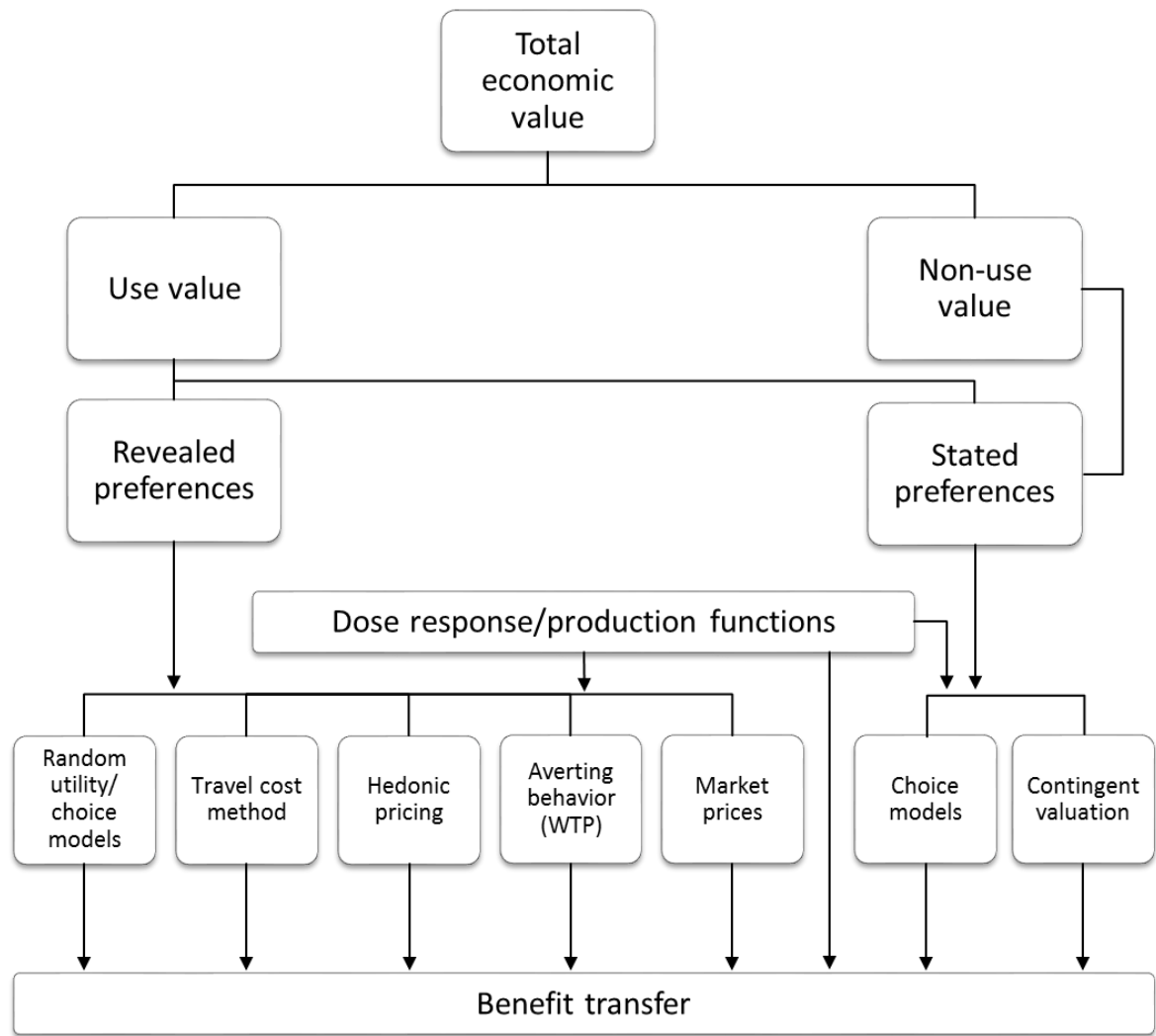


Figure 1. The total economic value framework including the grouping of valuation methods (Pearce et al., 2006).

Although a number of methods are available for valuation (Figure 1), A lack of knowledge of the interactions affecting the production of ecosystem services is cited as a major concern for economic analyses (Bateman et al., 2011), and this has certainly been an issue for sustainable stormwater management as a barrier to implementation (Sharma et al., 2016). In Germany, monetary valuations of ecosystem services are lacking in the planning of projects (Meyerhoff and Petschow, 2014), although recent research has shown progress in the uptake of the ecosystem service approach in the planning of public projects (Hansen et al., 2015). Although some stakeholders may view monetary valuations cautiously, policy makers in the water management sector generally acknowledge the transparency and efficiency in decision making through the valuations and mostly show positive attitudes towards the approach (Dehnhardt, 2013). This is an

important consideration for urban areas, as quantifying and valuing the ecosystem services, monetarily or otherwise, can improve cost-efficient planning (Rode et al., 2017).

Although monetary valuations for CBA approaches do merit many strengths, they are not free of dispute. There exist numerous arguments against the monetary valuation of ecosystem services and the presentation of the numerous ecosystem effects as a single number in a CBA (Gómez-Baggethun and Ruiz-Pérez, 2011; Gowdy et al., 2010; Kallis et al., 2013; Spangenberg and Settele, 2010). However, some of these arguments have been refuted on the basis of pragmatism (Kallis et al., 2013), because the common unit of measures (i.e., monetary value) provides the opportunity to compare various alternatives against the costs of implementation given a range of agents that accrue benefits (e.g., Gerner et al., 2018).

3. Introduction to the manuscripts

This dissertation is composed of three manuscripts. Table 2 categorizes the manuscripts according to publication status and journal ranking and displays the total points achieved with the manuscripts for this dissertation. Manuscript one, published in *Ecological Economics*, develops the methodology for valuation and analyzes the economic feasibility of three scenarios of sustainable urban drainage systems by economically valuing the ecosystem services thereof. Manuscript two, accepted for publication, analyzes the use of different city-scale adaptation scenarios in addressing the urban heat island effect while simultaneously valuing the ecosystem services thereof. Lastly, manuscript three has passed the desk reject at *Ecological Economics* and takes a finer-scale approach at valuing reductions in the urban heat island effect with sustainable stormwater management scenarios. This dissertation totals three manuscripts and 2.9 points attained through the publication statuses.

Table 2. Categorization of the manuscripts and total points achieved.

	Manuscript one	Manuscript two	Manuscript three
Title	Are neighborhood-level SUDS worth it? An assessment of the economic value of sustainable urban drainage system scenarios using cost-benefit analyses	A cost-benefit analysis of implementing urban heat island adaptation measures in small and medium-sized cities in Austria	The potential of stormwater management in addressing the urban heat island effect: An economic valuation
Authors	Johnson, D. & Geisendorf, S.	Johnson, D., See, L., Oswald, S. M., Prokop, G. & Krisztin, T.	Johnson, D., Exl, J. & Geisendorf, S.
Publication status	Published in: <i>Ecological Economics</i>	Accepted in: <i>Environment and Planning B: Urban Analytics and City Science</i>	Passed desk reject: <i>Ecological Economics</i>
Journal ranking	CNRS: A	CNRS: B	CNRS: A
Points achieved	$3 / 2 = 1.5$	$2 / 5 = 0.4$	$3 / 3 = 1$
Total points	2.9		

A further portrayal of the manuscripts contained in this dissertation is presented in Table 3 in order to show the differences in the CBAs, spatial scales and defining characteristics.

Table 3. Comparison of the manuscripts in terms of the approaches of the cost-benefit models.

	Manuscript one	Manuscript two	Manuscript three
Study site	Pankow neighborhood, Berlin, Germany	Mödling, Klagenfurt and Salzburg, Austria	Pankow neighborhood, Berlin, Germany
Measures analyzed	Sustainable urban drainage systems	Green infrastructure (Green City) High albedo surfaces (White City) Combination of Green and White City	Green infrastructure measures of sustainable urban drainage systems
Type of CBA	Financial and social	Social	Social
Time horizon	50 years	50 years	50 years
Discount rate	Financial: 3% Social: 3%	Social: 4.1%	Dual discount: Financial: 3% Ecosystem services: 2.1%
Sensitivity analysis	20% variations in parameters vs 20% variation in NPV	Monte Carlo analysis of sensitive parameters	Monte Carlo analysis of sensitive parameters

In manuscript one, the basis methodology for valuing ecosystem services of SUDS is developed, and three different scenarios of implementation for a study site in a neighborhood of Pankow, Berlin, are compared both financially and economically. The SUDS scenarios included the measures of green roofs, façade greening, tree drains, swales, trench systems, ponds, permeable pavement, rainwater harvesting and retention soil filters. Several of these measures fall under the umbrella of green infrastructure, but others are specifically designed for the improved natural cycling of water in urban areas, which imply the application of SUDS (Fletcher et al., 2015). The scenarios were developed based on technically feasible combinations of the different measures to address the goals of three independent groups of stakeholders involved in the planning process (Matzinger et al., 2017). Given the different rates of application of the individual measures, the scenarios produce contrasting levels of benefits in terms of the overall goal

of reduced stormwater runoff as well as the ecosystem services. The ecosystem services are valued according to the classification developed in TEEB (TEEB – The Economics of Ecosystems and Biodiversity, 2011) and included the services of groundwater recharge, drink water savings, runoff reduction, air quality improvements, carbon dioxide storage and sequestration, energy savings, increased building longevity, habitat creation and aesthetic improvements (Table 4). For the CBA, both a financial and economic analysis is carried out, and four indicators are chosen to investigate the economic feasibility: the NPV, the BCR, and the benefit and cost efficiencies. The sensitivity of the cost-benefit model is tested by investigating the percentage change in the NPV given a percentage change in each of the main parameters.

Table 4. List of ecosystem services valued, types of benefits and the valuation methods of each of the manuscripts.

				Manuscripts		
				1	2	3
	Ecosystem services	Type of benefit	Valuation method			
Provisioning	Groundwater recharge	Social	Market price	✓		
	Drinking water saved	Private	Market price	✓		
Regulating	Climate regulation					
	Heat-related mortality reduction	Social	Damage cost avoided		✓	✓
	Heat-related mortality reduction	Social	Damage cost avoided		✓	✓
	Reduced productivity loss	Social	Damage cost avoided		✓	
	Runoff reduction					
	Rainwater fee	Private	Market price	✓	✓	✓
	Runoff reduction	Social	Benefit transfer (choice experiments)	✓		
	Air quality improvements	Social	Damage cost avoided	✓	✓	✓
	CO ₂ storage and sequestration	Social	Damage cost avoided	✓	✓	✓
	Energy savings					
	Heating savings	Private	Market price	✓	✓	✓
	Indoor cooling	Social	Replacement cost	✓	✓	✓
	Externalities of heating	Social	Damage cost avoided	✓	✓	✓
Supporting	Increasing building longevity					
	Roof longevity	Private	Market price (replacement)	✓	✓	✓
	Façade longevity	Private	Market price (replacement)	✓		✓
	Habitat creation	Social	Replacement cost	✓	✓	✓
Cultural	Aesthetic improvements					
	Property value (w/ façade greening)	Private	Benefit transfer (hedonic price)	✓		✓
	Property value (w/ green roof)	Private	Benefit transfer (hedonic price)	✓	✓	✓

As manuscript one does not account for the value of reducing the urban island effect, manuscript two and three both investigate this value in two separate studies. Manuscript two focuses on small and medium-sized cities in Austria and investigates the economic feasibility of city-wide adaptation scenarios for the urban heat island effect. The “White City” scenario with highly reflective materials for roofs, streets and facades is compared to the “Green City” scenario incorporating green roofs, low vegetation and urban trees, and a final scenario combines both approaches. In all scenarios, the services relating to urban heat island mitigation are valued according to the reduced heat-related mortality and morbidity as well as reduced productivity loss, whereas in the “Green City” and combined scenarios, the ecosystem services of green measures are additionally valued (Table 4). This manuscript introduces a more detailed sensitivity analysis by testing the sensitivity of the whole cost benefit model given distributions of parameters with higher uncertainty or variation in a simulated Monte Carlo approach.

In the third manuscript, scenarios of SUDS implementation from the first manuscript are put into focus, and only those measures that bring about changes in the urban heat island effect are analyzed, termed in this manuscript as urban green infrastructure. This manuscript investigates how addressing stormwater management with SUDS scenarios not only supports the provision of ecosystem services that were analyzed in the first manuscript, but also improve the provision of heat regulation with the implementation of green roofs, façade greening and urban trees. Furthermore, this manuscript incorporates recent advances in the discounting of ecosystem services (Baumgärtner et al., 2015; Drupp, 2018), in which separate discount rates are used for the economic indicators in calculating the benefits in terms of ecosystem services and financial returns. Given low growth rates of ecosystem service provision and low substitutability, theory suggests according to the Ramsey model that discount rates for ecosystem services should even converge to a low value (Zhu et al., 2019). Therefore, the framework for discounting ecosystem services was incorporated into the results of this manuscript. Given the differences in the discount rate as well as uncertainty in parameters that lead to large variation in the NPV (e.g., value of a statistical life), many parameters of the cost-benefit model were tested in a Monte Carlo analysis procedure similar to manuscript two.

4. Manuscripts

4.1. Are neighborhood-level SUDS worth it? An assessment of the economic value of sustainable urban drainage system scenarios using cost-benefit analyses

Manuscript one

The manuscript is published as:

Johnson, D. & Geisendorf, S. (2019). Are neighborhood-level SUDS worth it? An assessment of the economic value of sustainable urban drainage system scenarios using cost-benefit analyses. *Ecological Economics* 158: 194-205. DOI:10.1016/j.ecolecon.2018.12.024

4.2. A cost-benefit analysis of implementing urban heat island adaptation measures in small and medium-sized cities in Austria

Manuscript one

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4.3. The potential of stormwater management in addressing the urban heat island effect: An economic valuation

Manuscript three

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5. Discussion

With the overall aim of valuing the ecosystem services of green infrastructure and extending the methodology thereof, this dissertation has approached the research aim in several different contexts and on different spatial scales. Manuscript one analyzes three different scenarios of SUDS for their economic feasibility in a neighborhood-level analysis by valuing various ecosystem services, although insufficient methods were identified for valuing the mitigation of the urban heat island effect. This caveat provided the preliminary research aims for manuscript two and three, which investigated the monetary valuation of urban heat island mitigation by means of city-wide green and white infrastructure scenarios and neighborhood-level SUDS measures, respectively. In the following, the key results of the manuscripts are discussed in light of wider implications for ecosystem service valuation.

5.1. Key results

With a focus on stormwater management, manuscript one proposes a methodological framework for valuing the numerous ecosystem services of SUDS. Although the valuation literature is rich, the manuscript demonstrates the novelty of the approach for assessing whole neighborhood-level strategies. Although the framework is geared towards SUDS, the valuation methods stem from literature that has focused on several specific measures which are common to general green infrastructure strategies (e.g., green roofs). The study finds that the costs of such SUDS scenarios outweigh the benefits and generate considerable societal value in the form of ecosystem services. Not all scenarios result in economic feasibility, which may be reasoned with the high costs of measures, such as façade greening. Although façade greening brings about significant economic value in terms of aesthetic quality (Perini and Rosasco, 2013), a significant contribution to mitigating urban heat islands is also attainable (Saaroni et al., 2018) as well as reducing extremely high indoor temperatures (von Tils, 2017). However, the methodology necessary for economically evaluating the effects on urban heat islands of such scenarios are less developed, and this provided the grounds for research in manuscript two and three.

In manuscript two and three, two different approaches for quantifying the value of urban heat island mitigation of green infrastructure scenarios are developed and

incorporated into CBAs for different cities. Although both manuscript two and three integrate the basis methodology for valuing the urban ecosystem services of green infrastructure used in manuscript one, each of the two manuscripts further develop the methodology by including novel aspects into the CBA.

Manuscript two evaluates the economic feasibility of different scenarios of urban heat island adaptation at the city scale for small- and medium sized cities in Austria. Analyses of urban heat island effects in such cities is lacking in the literature (Oswald et al., 2020) as well as the development of green infrastructure planning and the analysis of ecosystem services (Shackleton et al., 2018). The scenarios of urban heat island adaptation portray different possibilities of mitigating the urban heat island effect through implementing green infrastructure (i.e., Green City approach), implementing measures for increasing the albedo of surfaces (i.e., White City approach), or implementing a combination of green and white measures. The main findings of this manuscript highlight the economic feasibility of all of the approaches. Although pursuing green measure scenarios incurs significantly higher costs, even greater benefits are accrued, as shown by higher NPVs and BCRs of those scenarios. The core finding is made apparent by the multifunctionality that is engendered in these scenarios (Hansen and Pauleit, 2014): by addressing the urban heat island effect with green infrastructure, not only is the effect mitigated to certain degree, but many other urban issues are solved simultaneously. Although the urban heat island effect may be mitigated to a higher degree in the White City approach by increasing the albedo of surfaces, the spaces taken up by the measures do not support the other regulating, supporting, and cultural ecosystem services provided by green measures.

Lastly, manuscript three also tackles the issue with a lack of economic valuations of urban heat island mitigation through green infrastructure but approaches the analysis at a finer scale. The study compared three different scenarios of sustainable stormwater management to assess the urban heat island mitigation effect and proposed a methodology for valuing this mitigation. Furthermore, the study incorporates recent advances in the discounting of ecosystem services (Baumgärtner et al., 2015; Drupp, 2018) and further develops the sensitivity analysis pursued in manuscript two in order to account for occurrences of risk and uncertainty in the data. The results of the CBA demonstrate positive economic grounds for project approval of all three scenarios. However, the core finding of the analysis is highlighted in the positioning of the green measures in areas in

which the vulnerability to urban heat islands is high, thus boosting the societal value of the scenarios and increasing the NPV.

5.2. Monetary valuation of ecosystem services

Specifically for manuscript one and three, the scenarios for addressing stormwater management were developed with the input of local stakeholders. In three independent rounds, the scenarios were constructed based on the physical feasibility to achieve the local issues relating to stormwater management, urban heat, biodiversity, resource efficiency, groundwater, quality of free space and building-level benefits (Matzinger et al., 2017). Therefore, the scenario development was based on a participatory approach, which further improves the planning process concerning urban ecosystem services and is often still lacking in implementation (Haase et al., 2014).

Since the participatory process led to the creation of the scenarios, the arguments against the monetary valuation of the urban ecosystem services are partially neutralized for these studies. Critics of the monetary valuation of ecosystem services argue that there is a lack of objectivity in the valuations (Spangenberg and Settele, 2010) or that policy recommendations should not be made based on a single economic number (Gowdy et al., 2010), as there might be numerous non-economic benefits that could be recognized and valued in other ways than monetary valuations (Baveye et al., 2013). However, the first and third manuscripts propose the monetary valuations of the ecosystem services produced in the scenarios already developed with the support of stakeholder input. Given that independent stakeholder input generated three starkly contrasting scenarios, the CBAs in the two manuscripts demonstrate the sort of the benefits that residents would obtain and provide the opportunity to rank the scenarios directly according to the values of the residents.

This methodology satisfies the criteria laid out in Kallis et al.'s (2013) framework for deciding to carry out monetary valuations of nature, who proposed questioning whether the valuations improve the environmental conditions, reduce inequalities, suppress other valuation techniques and if the valuations would induce commodification that coincidentally degrades the socio-environments in question. As the valuations in the manuscripts do endeavor for improving the environmental conditions and reducing inequalities by identifying, recognizing and subsequently portraying all the additional benefits of sustainable stormwater management, these criteria are considered to be

satisfied. The valuations in the two manuscripts follow the initial scenario development by stakeholder input, which does not suppress other valuation techniques but rather integrates them. Furthermore, no foreseeable commodification of the services can be assumed, as the valuations are only used for planning purposes.

Manuscript two takes a slightly different approach to the analysis of urban ecosystem services as the scenarios are designed to plan for the adaptation to the urban heat island effect. Nonetheless, the scenarios represent the maximum feasible application of different sets of measures (i.e., Green City measures such as green roofs and trees, White City measures such as high albedo roofs and surfaces, and a combination of the two) to indicate to urban planners and city officials the maximum contribution of the measures to mitigate the effects of urban heat islands. The CBAs in the manuscript serve to indicate the implications as costs and benefits for society. Also relying on the pragmatism approach of Kallis et al.'s (2013) framework, the valuations in this study also satisfy the criteria, as the study attempts to improve the environmental conditions and reduce inequalities by identifying, estimating and valuing the additional ecosystem services of urban heat island adaptation while not suppressing other possible valuation techniques and instigating the commodification of the services. Moreover, by valuing the urban ecosystem services of urban heat island mitigation in monetary terms, it is possible to demonstrate on economic grounds the difference between investing in Green City and White City approaches, which is one of the key insights of the manuscript: investing in Green City approaches simultaneously addresses many other critical environmental and health issues in urban areas than solely investing in White City approaches and engenders multifunctionality in the planning process (Hansen and Pauleit, 2014).

5.3. Implications

Given the several research gaps addressed within each of the manuscripts at the crossroads of environmental management and economics, not only implications for research can be subsumed but also practical implications can be put forward. In the following, the implications arising from each of the manuscripts is discussed.

The results of the three manuscripts provide important implications for urban planners and policy makers in the planning process of multiple urban issues. Using the basis set of methods for economically valuing the ecosystem services of SUDS in the first manuscript, economic grounds for project approval can be developed. Such analyses

would align with water management planning within the Water Framework Directive if such CBAs were to be required (European Commission, 2000). This would answer calls for more uptake of the ecosystem service concept and the economic valuation thereof as well as improve the connection between the scientific and practical dimensions (Haase et al., 2014). Through the incorporation of the urban ecosystem service concept, cities can begin to address resilience and sustainability on several fronts (McPhearson et al., 2015). It is thus important to recognize the value of such services as disregarding urban ecosystems can entail high economic costs in the long term (Gómez-Baggethun and Barton, 2013). Especially concerning climate change, implementing green infrastructure may reduce the uncertainty involved in planning for mitigation and adaptation (Demuzere et al., 2014).

In terms of research implications, the manuscripts in this dissertation further the research streams on ecosystem services in several ways. First, the neighborhood-level approach to the economic valuation of ecosystem services in the first and second manuscripts provide the means for evaluating services on similar spatial scales to those used in actual urban planning (Larondelle and Lauf, 2016). This resonates with issues that have been raised among ecosystem service researchers that assessments at various spatial scales may not end up being utilized in practice since the information does not transfer to analogous urban planning scales (Andersson et al., 2015). Especially the neighborhood-level evaluation of ecosystem services is underrepresented in the literature (Haase et al., 2014). Although the third manuscript analyzes scenarios of implementation at the level of the city, the cities under study were small and medium-sized, and the planning for the adaptation to the urban heat island effect was taking place at this scale. Therefore, the planners and city officials could use the city-level CBA for understanding the societal welfare implications of the different scenarios of implementation.

Secondly, although the analyses integrated various economic methods to obtain values specific for the study sites, the analyses provided a comprehensive framework for estimating the economic value of several measures in the concerted provision of ecosystem services. As the first and third manuscripts addressed stormwater management, this framework furthers the research on realizing the economic valuation of ecosystem services resulting from stormwater management systems. Previous literature has often only analyzed the ecosystem services of single measures, and some studies have performed CBAs for whole stormwater management systems but have excluded the

valuation of ecosystem services (Liu et al., 2016). Therefore, these manuscripts build on works that have classified ecosystem services of stormwater management (Mak et al., 2017; Prudencio and Null, 2018) by amalgamating the economic means to value them. Furthermore, the second and third manuscripts estimate the value of urban heat mitigation services of green infrastructure, which is an underdeveloped section of the literature on ecosystem service valuation, especially in the stormwater management planning (Venkataramanan et al., 2019). Given that increased heat-related mortality is a major societal consequence of future climate change (Gasparrini et al., 2017) and that green infrastructure is posited as an important solution to mitigating and adapting to increased urban temperatures (Stone et al., 2014), these manuscripts are propounded to further the research in the economic valuation of scenarios addressing these human health impacts.

6. Limitations and future research outlook

Despite the advances made in the analysis and the monetary valuation of ecosystem services of green infrastructure in different contexts, the manuscripts in this dissertation impart several limitations and directions for future research.

First, one major limitation of manuscript one is the lack of the necessary methodology for estimating the value of urban heat island mitigation. Many articles have found green measures, such as green roofs and facades, to make positive contributions to mitigating the urban heat island effect (Besir and Cuce, 2018). Urban trees also make substantial contributions to cooling and providing shade for urban residents (von Tils, 2017). However, at the time of study of manuscript one, the methodology to evaluate this regulating urban ecosystem service was lacking and could not have been incorporated into the analysis. Although one study in Berlin demonstrated slight improvements of green façades on urban ambient temperature (Jänicke et al., 2015), this study investigated only one façade, whereas the scenarios in the manuscript greened much larger areas. With a simulated urban climate model, a further study in Berlin showed that greening roofs can decrease urban temperatures (Schubert and Grossman-Clarke, 2013), which supports empirical evidence obtained just northeast of Berlin by Köhler and Kaiser (2019). Therefore, further analyses were deemed necessary to understand how to include the results of such analyses in the CBAs that value urban ecosystem services of green infrastructure, providing the impetus for economically investigating urban heat island

mitigation through urban climate models (i.e., in manuscript two) and through finer scale mitigation efforts (i.e., manuscript three).

Second, the CBAs conducted in each of the manuscripts considered total social benefits and costs and did not account for the distribution to individual cost carriers and beneficiaries. The costs of some of the measures must be borne by the city, such as the case with street trees. However, many of the measures, such as green roofs and façade greening, would have to be implemented by individuals or housing agencies. This creates difficulties in understanding the financial sustainability of investments from the side of the individual or the city. However, the goals in each of the manuscripts were to estimate the total net welfare changes to society, which was done in the social CBAs of the manuscripts. These analyses are important for investigating the value accruing to the whole society and whether economic feasibility is achieved, that is, whether the improved welfare of society outweighs the costs to be borne, in order to generate public support for policy actions (Vandermeulen et al., 2011).

Another limitation that ranges through the three manuscripts is the comprehensive understanding and accuracy of the value of green infrastructure to society. The methods of economic valuation used in the manuscripts comprised revealed preference as well as stated preference methods. For example, in the first manuscript, improvements in water quality due to stormwater runoff reduction is estimated through stated preferences (i.e., willingness to pay), whereas the increase in property values is computed through the revealed preference method of hedonic pricing. Revealed preference methods provide observational evidence of the value of goods and services capitalized into market prices, which generally provides the possibility of capturing use values, whereas stated preference methods can capture both use and non-use values by directly asking respondents for their willingness to pay (Champ et al., 2017). Given that green infrastructure provides numerous ecosystem services for which values might not be capitalized into market prices, stated preference methods might provide further economic grounds for investing in green infrastructure. A few studies have already investigated the value of green infrastructure using discrete choice experiments as a stated preference method and have obtained a positive willingness to pay for various attributes such as reduced summer temperatures, improved water quality and recreational opportunities (Brent et al., 2017). Although stated preference methods, such as discrete choice experiments, are not without their own limitations (Spangenberg and Settele, 2010),

integrating such methods in the future with other available methods can certainly improve the accuracy and inclusion of the multiple dimensions of value that can be attributed to green infrastructure (Jacobs et al., 2018).

7. Conclusion

Urban areas are increasingly affected by a plethora of issues ranging from stormwater management to urban heat islands, due to growing urban populations and high rates of urbanization. Given these issues, the supply of ecosystem services in urban areas are declining at high rates, presenting great challenges for urban populations to maintain societal welfare and wellbeing. However, great promise is seen with solutions in green infrastructure, which can replenish the provision of numerous ecosystem services. This dissertation aimed to analyze the ability of various constellations of green infrastructure to provide ecosystem services in urban environments and generate significant social value.

As urbanization progresses, natural surfaces become increasingly sealed leading to challenges in managing stormwater runoff and preventing the degradation of receiving water bodies. The first manuscript analyzed the costs and benefits of a subset of green infrastructure addressing stormwater management, termed SUDS, by valuing the additional ecosystem services generated through numerous green measures at the neighborhood level. Although costs of such systems are high, economic feasible combinations can be achieved, and stormwater issues are improved while simultaneously providing significant societal value through ecosystem services. Through the neighborhood-level approach, this methodology can be used in the urban planning process. Although the literature is growing in this field, numerous studies focus only on single measures or lack the framework for estimating and valuing several ecosystem services. Although the first manuscript addressed this gap, heat regulation services of green infrastructure could not be evaluated at the current state, and further research was warranted for estimating these values to society.

Given that urbanization also exacerbates the urban heat island effect, it is important to evaluate the urban heat regulation services of green infrastructure. In order to value changes in urban heat islands, the second and third manuscripts analyzed the economic feasibility of adaptation planning approaches in two different spatial scales. In the second manuscript, the application of green infrastructure in small and medium-sized

cities demonstrated economically feasible results while providing numerous additional ecosystem services. Although the Green City approach and the combined green and white measures incur high costs, higher benefits are obtained with these scenarios compared to the White City approach that solely addresses the urban heat island effect. This result highlights the multifunctionality of the approaches that incorporate the provision of ecosystem services and further demonstrates the need for the inclusion of ecosystem service assessments of green infrastructure in the planning of urban heat island adaptation.

The importance of including the urban heat regulation services of green infrastructure was also made apparent through the study in the third manuscript. Given that green infrastructure measures such as green roofs and tree drains can incur tremendous costs, it is important to include in the economic analysis those significant benefits to society, such as reducing heat-related mortality and morbidity. Moreover, planning the implementation of such measures should include an analysis of where the accrual of the benefits is highest, namely where the exposure to heat risk is the highest, to further improve the net welfare improvement to society.

With the help of the methods in each of the manuscripts of this dissertation, urban planners and decision makers can improve the transparency and efficiency in project development and policy making. By including the economic valuation of ecosystem services, the improvement of the health, wellbeing and welfare of urban societies is considered in the planning process, and, given the results of the manuscripts in this dissertation, the improvement in societal welfare through green infrastructure implementation can certainly outweigh the costs. Furthermore, by including such analyses, the groundwork can be laid for engendering multifunctionality in the planning process, which becomes of increasing importance given the horde of challenges brought about through urbanization.

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