



## Review

# A systematic review of the human health and social well-being outcomes of green infrastructure for stormwater and flood management

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## ABSTRACT

**Background:** The increase in frequency and intensity of urban flooding is a global challenge. Flooding directly impacts residents of industrialized cities with aging combined sewer systems, as well as cities with less centralized infrastructure to manage stormwater, fecal sludge, and wastewater. Green infrastructure is growing in popularity as a sustainable strategy to mimic nature-based flood management. Although its technical performance has been extensively studied, little is known about the effects of green stormwater infrastructure on human health and social well-being.

**Methods:** We conducted a multidisciplinary systematic review of peer-reviewed and gray literature on the effects of green infrastructure for stormwater and flood management on individuals', households', and communities' a) physical health; b) mental health; c) economic well-being; and d) flood resilience and social acceptance of green infrastructure. We systematically searched databases such as PubMed, Web of Science, and Scopus; the first 300 results in Google Scholar; and websites of key organizations including the United States Environmental Protection Agency. Study quality and strength of evidence was assessed for included studies, and descriptive data were extracted for a narrative summary.

**Results:** Out of 21,213 initial results, only 18 studies reported health or social well-being outcomes. Seven of these studies used primary data, and none allowed for causal inference. No studies connected green infrastructure for stormwater and flood management to mental or physical health outcomes. Thirteen studies were identified on economic outcomes, largely reporting a positive association between green infrastructure and property values. Five studies assessed changes in perceptions about green infrastructure, but with mixed results. Nearly half of all included studies were from Portland, Oregon.

**Conclusions:** This global systematic review highlights the minimal evidence on human health and social well-being relating to green infrastructure for stormwater and flood management. To enable scale-up of this type of infrastructure to reduce flooding and improve ecological and human well-being, widespread acceptance of green infrastructure will be essential. Policymakers and planners need evidence on the full range of benefits from different contexts to enable financing and implementation of infrastructure options, especially in highly urbanized, flood-prone settings around the world. Therefore, experts in social science, public health, and program evaluation must be integrated into interdisciplinary green infrastructure research to better relate infrastructure design to tangible human outcomes.

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## 1. Introduction

### 1.1. Urban flooding

Urban flooding is a growing challenge due to increasing urbanization, population growth and pressures on land use (CRED, 2015; Hallegatte and Corfee-Morlot, 2011). This challenge is exacerbated by climate change, which is predicted to increase both rainfall frequency and intensity (IPCC, 2012; Schneider et al., 2000). Indeed, the consequences of catastrophic flooding have been well documented globally, including economic losses (Hallegatte et al., 2013; NOAA, 2018), adverse physical and mental health outcomes (Ahern et al., 2005; CRED, 2015; Du et al., 2010; Saulnier et al., 2017), and intensification of social inequalities (Ajibade et al., 2013; Chatterjee, 2010; Nur and Shrestha, 2017; Walker and Burningham, 2011).

While the effects of catastrophic flooding events are more conspicuous, the consequences of chronic, localized stormwater-related flooding are also of major concern (Center for Neighborhood Technology, 2014; Jha et al., 2012; Winters et al., 2015). High-intensity rain events can trigger low-grade flooding of streets, homes and basements, particularly in cities with aging combined sewer systems, poor drainage, and extensive impervious surfaces (Chang et al., 2018; Douglas et al., 2010; Ranger et al., 2011). This type of urban flooding can result in economic losses, degrade natural systems, and affect human productivity, health, and psychosocial well-being (Kennedy et al., 2008).

### 1.2. Green infrastructure for stormwater and flood management

One increasingly popular set of stormwater and flood management strategies aims to mimic natural hydrological systems to manage runoff and flooding in built environments. Such “green infrastructure” is described as part of several umbrella terms, such as blue-green infrastructure (BGI), Sustainable Drainage Systems (SuDS), Low Impact Development (LID), water sensitive urban design (WSUD), Best Management Practices (BMPs) for stormwater runoff, natural or nature-based infra-

structure, and ecosystem-based adaptation (EbA) (Bartasaghi Koc et al., 2017; Fletcher et al., 2015; Liao et al., 2017; McKissock et al., 1999; Mell, 2013; Wright, 2011; Young et al., 2014). Here, we collectively refer to all of these concepts as green infrastructure (GI).

### 1.3. Rationale for the review

GI for stormwater and flood management has been studied extensively by engineers, urban planners, ecologists, and economists, but with relatively limited integration between the fields, or attention to the consequences beyond physical infrastructure or environmental impacts. There is indeed a large body of evidence on the ability of GI to capture stormwater and reduce runoff, improve water quality, and achieve environmental benefits (Eckart et al., 2017; Gill et al., 2007; Moore et al., 2016). However, there is far less systematic documentation of outcomes directly related to human health and social well-being. Reviews on the broader relationships between nature or greenspace and human health have highlighted the importance of this connection, but also the preponderance of observational and cross-sectional studies that lack the ability to establish causality (Demuzere et al., 2014; Hartig and Kahn, 2016; Houghton and Castillo-Salgado, 2017; Houlden et al., 2018; Jackson, 2003; Jackson et al., 2013; Lachowycz and Jones, 2011; Sandifer et al., 2015; Tzoulas et al., 2007; Wolf and Robbins, 2015). These reviews summarize studies on green building design or general green space, but do not describe studies specifically on stormwater and flood management. There is also a wide body of literature on the importance of human perceptions, knowledge, and behavior on flood risk management (Aerts et al., 2018; Terpstra et al., 2009; Vávra et al., 2017), but the ability of GI projects to improve these human dimensions is unclear.

The study of human health and social well-being is complex, with interconnected explanatory factors and outcomes. To disentangle the different ways in which health and well-being can be affected by GI designed for stormwater and flood management, we explored four pathways (Fig. 1):

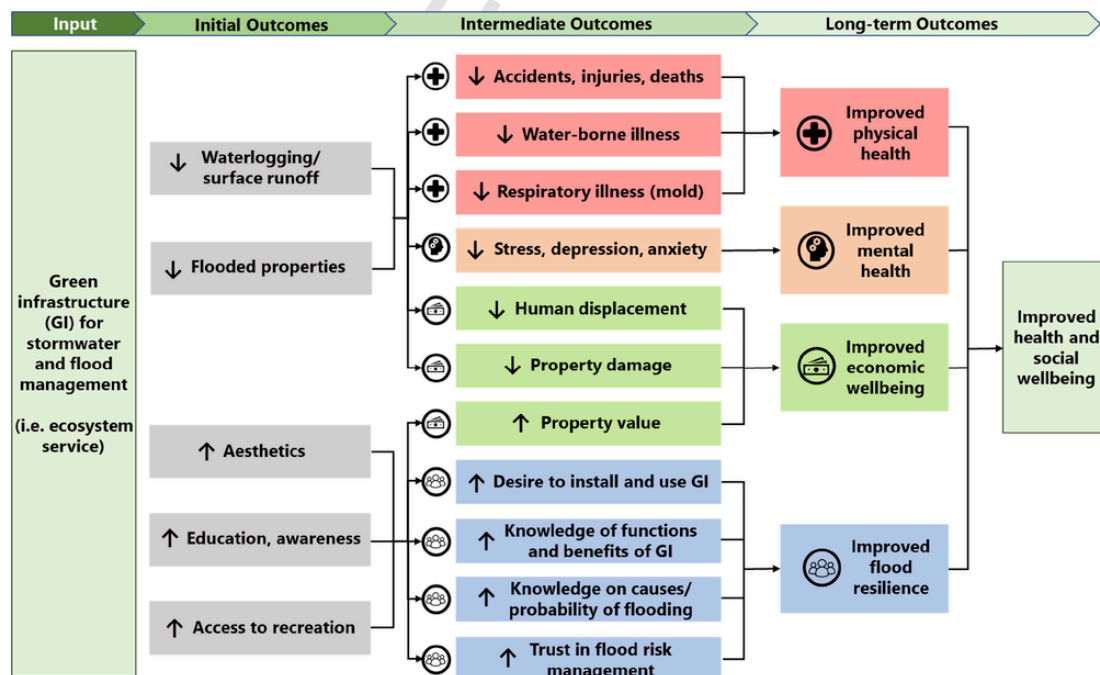


Fig. 1. An illustrative list of hypothesized causal pathways between green infrastructure (GI) projects and their initial, intermediate, and long-term outcomes for human health and social well-being. Adapted broadly from BenDor et al. (2018); Martín-López et al. (2014); Millennium Ecosystem Assessment, 2005. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

- Physical health (e.g., waterborne or respiratory illness, accidents, injuries, deaths)
- Mental health (e.g., stress, anxiety, depression)
- Economic well-being (e.g., property damage/value, human displacement and lost productivity)
- Flood resilience and social acceptance of GI (e.g., knowledge and perceptions of flood risk and GI, desire to install or use GI)

To identify empirical support for the hypothesized causal links between GI designed for stormwater and flood management and human health and social well-being outcomes, we conducted a multidisciplinary systematic literature review. We hypothesized that GI designed for stormwater and flood management has a positive effect on these four pathways for individuals, households, and communities.

With this review, we aim to inform the design of multidisciplinary, comprehensive evaluations of GI projects, thereby enabling decision-makers to identify an effective suite of solutions to mitigate urban flooding.

## 2. Methods

### 2.1. Operationalization of concepts

In defining GI for stormwater and flood management, we referred to the larger-scale concept of GI as natural areas that provide flood protection and water quality benefits to cities (Chenoweth et al., 2018; Mell, 2013; U.S. EPA, 2017; Young et al., 2014). We also included neighborhood- and site-scale GI within cities as infrastructure that “uses vegetation, soils, and other elements and practices to restore some of the natural processes required to manage water and create healthier urban environments” (U.S. EPA, 2017). Using this inclusive definition, we considered health and social well-being outcomes related to the following types of GI: rain gardens, green roofs, bioswales, greenstreets, cisterns, rain barrels, reconstructed wetlands, urban waterways, riparian corridors, natural green spaces such as urban parks, urban forests, tree canopy, and natural preserves, and pervious pavement and subsurface detention systems.

Although we restrict our focus in this review to GI installed with the primary purpose of managing stormwater and flooding, the multiple co-benefits of GI installations are important to note. For example, several of the GI types we consider in this review, such as urban tree canopy, can simultaneously serve other functions, such as reducing the urban heat island effect (Block et al., 2012), improving air quality (Pugh et al., 2012), or increasing drought resilience (Kloos and Renaud, 2016). In this paper, we focus on human health and well-being benefits from the perspective of flooding.

Ecosystem services are defined both as the part of the ecosystem that produces human well-being (Fisher et al., 2009) and the benefits that people derive from an ecosystem (Millennium Ecosystem Assessment, 2005). The more widely used Millennium Ecosystem Assessment definition, however, risks conflating the concepts of an input or service (e.g., an urban forest), the most immediate outcomes or benefits it has the potential to produce (e.g., flood protection, access to greenspace), and the intermediate or longer-term health and social well-being outcomes that can occur as a result. Therefore, we follow Fisher et al.’s (2009) definition of ecosystem services in our conceptualization of the relationship between GI for stormwater and flood management and the health and social well-being outcomes that are the primary measures investigated in this review.

### 2.2. Search strategy

A protocol for this systematic review is registered in PROSPERO (registration number: CRD42018094256). We searched for scientific and gray literature (reports, theses, dissertations, white papers) from the following databases between January and March 2018, with no restrictions on language, time period of the work, or document type: PubMed, Web of Science, Scopus, Embase, EBSCO Host, Proquest Dissertations and Theses, and Global Reference on the Environment, Energy, and Natural Resources (GREENR) Database. In addition, we extensively hand-searched references cited in included studies, the first 300 results in Google Scholar (Haddaway et al., 2015), and the websites of key organizations working or reporting on GI or nature-based infrastructure (Supplementary Table 1).

Our search terms were informed by prior reviews of GI definitions and typologies (Bartessaghi Koc et al., 2017; Young et al., 2014) and discussions with experts to capture the most commonly used terms. We used slightly different formulations of these search terms for each database; as an example, Table 1 illustrates the search strategy used in the Web of Science database. See Supplementary Table 1 for the complete search strategy used for each database.

### 2.3. Eligibility criteria and scale of review

In the initial search, any GI or greenspace project explicitly designed to manage stormwater or flooding from all contexts and settings was considered for inclusion. The urban/rural divide is less demarcated in some countries, and as such, we retained studies that met our eligibility criteria even if they were not in urban settings. Following standard systematic review guidelines (Higgins and Green, 2011), we then excluded reviews, commentaries, editorials, blog posts, publicity material, or news and magazine articles to maintain scientific objectivity.

To identify changes in our outcomes of interest (Fig. 1), we primarily considered experimental (e.g. randomized controlled trials) or quasi-experimental studies (e.g., pre-post design with a matched comparison group). We also included cross-sectional studies on quantitative associations between GI and changes in our outcomes of interest, provided they used localized retrospective data that could indicate changes over time in human health, economic or social well-being, or changes in values, perceptions, or interactions with GI or flood risk. For example, we included revealed preference studies that use secondary data to understand economic impacts based on real decisions, drawing “statistical inferences on values from actual choices people make within markets” (Boyle, 2003).

GI for stormwater and flood management can be implemented and operated at multiple scales (watershed, city, neighborhood, individual homes), but its impacts on human well-being manifest at the local scale. Therefore, although we included GI projects occurring at any scale, we retained our focus on health and social well-being outcomes

**Table 1**

Sample search strategy for the Web of Science database. See Supplementary Table 1 for full search strategy for each database.

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TS=(“Green infrastructure\*” OR “Natural infrastructure\*” OR “Eco\* service\*” OR “Nature based solution\*” OR “Eco\* based adaptation\*” OR “green space\*” OR “greenspace\*” OR “natural area\*” OR “low impact development\*” OR “low impact infrastructure\*” OR “best management practice\*” OR “rain garden\*” OR raingarden\*” OR “green roof\*” OR “blue roof\*” OR “permeable pavement\*” OR “bioswale\*” OR “greenstreet\*” OR streetscape\*” OR cistern\*” OR “rain barrel\*” OR “French drain\*” OR “dry well\*” OR “urban waterway\*” OR “urban wetland\*” OR “urban constructed wetland\*” OR “urban riparian corridor”\*)

AND TS=(stormwater OR “storm water” OR “rainwater runoff” OR “Urban runoff” OR “surface runoff” OR rain OR rains OR rainfall OR precipitation OR downpour OR waterlogging OR “water logging” OR flood\*)

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that are measurable at the individual, household, and neighborhood scale.

Several types of studies were excluded as outside the scope of this review. Studies on GI or greenspace that exclusively focused on non-stormwater or flood impacts (e.g., urban heat island effect) or that did not explicitly mention stormwater or flooding as their primary purpose were excluded (e.g., Alcock et al., 2014; Fonseca et al., 2014). Studies that only reported on the technical efficacy or performance of GI for stormwater or water quality were excluded unless they attempted to measure links to, or changes in, human health. As our focus was on primary research, we also excluded studies that modeled hypothetical scenarios of flooding or GI installations (e.g., Pregolato et al., 2016; Williams and Wise, 2009), and stated preference studies such as contingent valuation (e.g., Dumenu, 2013), where people are typically surveyed on their willingness to pay for different hypothetical scenarios. Finally, we also excluded studies that projected health or economic impacts using secondary data, such as life cycle assessments (e.g., Flynn and Traver, 2013; Li et al., 2018; McDuffie et al., 2015); while such studies can be useful for estimating health impacts at a higher level, this review focused on the local scale.

#### 2.4. Screening and selection process

A team of four researchers with backgrounds in public health, environmental science, and social policy (VV, DM, DP, DL) were involved in the title, abstract, and full text screening process of studies retrieved using the search strategy and those from additional sources (Liberati et al., 2009). First, 10% of titles were independently screened by all researchers to establish consistency. Decisions were compared, and where three out of four researchers were in concurrence with a “retain” versus “exclude” decision, that decision was treated as final. All other discrepancies were resolved through discussion as a group. The remaining titles were divided amongst researchers, given the large number of results expected from the searches. A similar process was repeated to screen abstracts. Only references that were not relevant to our broad definition of GI were excluded. Obvious duplicates were also excluded, as were references with multiple publication formats. For example, if we identified a journal article, thesis, and conference proceeding by the same authors using the same data, we only included the journal article. Full texts were then retrieved and screened. Ten percent of decisions were re-screened independently by another researcher in the team, and discrepancies were resolved through discussion as a group. The final set of studies was reviewed by the first author (VV) for inclusion in this review, to confirm that the study reported at least one outcome of interest (Fig. 1).

#### 2.5. Quality appraisal

Assessing study quality and strength of evidence is recognized as an essential component of systematically reviewing evidence (Higgins and Green, 2011). Various tools exist depending on study designs and research questions. We used a 14-point framework for multiple study designs that considers three categories: quality of reporting (six questions), minimizing risk of bias (five questions), and appropriateness of conclusions (three questions) (see Supplementary Table 2 and Venkataramanan et al., 2018). All questions received a score of 0, 0.5, or 1. Two researchers independently assessed study quality, and scoring discrepancies were resolved through discussion. Studies were rated from the perspective of social research methods as high quality (score of  $\geq 10$  to 14), medium quality (score  $\geq 5$  and  $< 10$ ), or low quality (score  $< 5$ ).

#### 2.6. Data extraction and analysis

Data were extracted into a standardized Microsoft Excel spreadsheet for assessment of study quality and reporting of basic descriptive data for each study. Descriptive information included author, title, publication year, country, study setting (urban/rural), GI types, study population, study design, study dates, other demographic information, project conditions, and measured outcomes. Given the heterogeneity of study designs and outcomes, we provide a narrative summary of the studies by types of outcomes measured.

### 3. Results

#### 3.1. Search results

In total, the search process resulted in 19,145 initial results from journal databases and 2062 results from the gray literature (Fig. 2). After removing duplicates, 14,955 titles were screened for inclusion. Of these, 4607 full-text documents were reviewed. During the full-text screen, studies were excluded for various reasons, such as only reporting on the technical performance of GI ( $n = 3044$ ), and being purely descriptive or not reporting data on changes in at least one outcome of interest ( $n = 578$ ). Ultimately, 18 studies reported at least one health or social well-being outcome illustrated in Fig. 1 and met inclusion criteria for this review.

#### 3.2. Quality appraisal

Two-thirds (67%) of the 18 included studies were rated as high quality. On average, studies scored high in the categories of quality of reporting (mean score 4.4 out of 6) and appropriateness of conclusions (mean score 2.5 out of 3). The lowest scores and greatest variation were in the category of minimizing risk of bias (mean score 3.2 out of 5). As most studies used secondary data, the quality appraisal framework was modified to give credit to any description of the original data source (e.g., nationally representative datasets or property sales databases), and the rigor of their data collection procedures. However, most studies did not report such details (see Supplementary Figure 1).

#### 3.3. Characteristics of the literature

Almost half of the included studies (44%) were based in Portland, Oregon in the Pacific Northwest region of the United States. A variety of GI types were represented, and almost all were in urban or sub-urban settings (Table 2). Only six studies (33%) collected primary data from the perspective of social research, such as surveys or interviews; three of these used a pre-post design to attempt to measure changes, whereas the rest were cross-sectional. None of the studies used experimental designs.

#### 3.4. Quantifying human health and social well-being outcomes of GI projects

##### 3.4.1. Changes in physical and mental health

Much has been written about the positive association between nature or greenspace and physical (Houghton and Castillo-Salgado, 2017; Salmond et al., 2016) and mental health (Houlden et al., 2018). However, we did not identify any studies that directly measured physical health or mental health outcomes relating to GI designed with the primary purpose of stormwater and flood management at the individual, household, or neighborhood scale (Fig. 3).

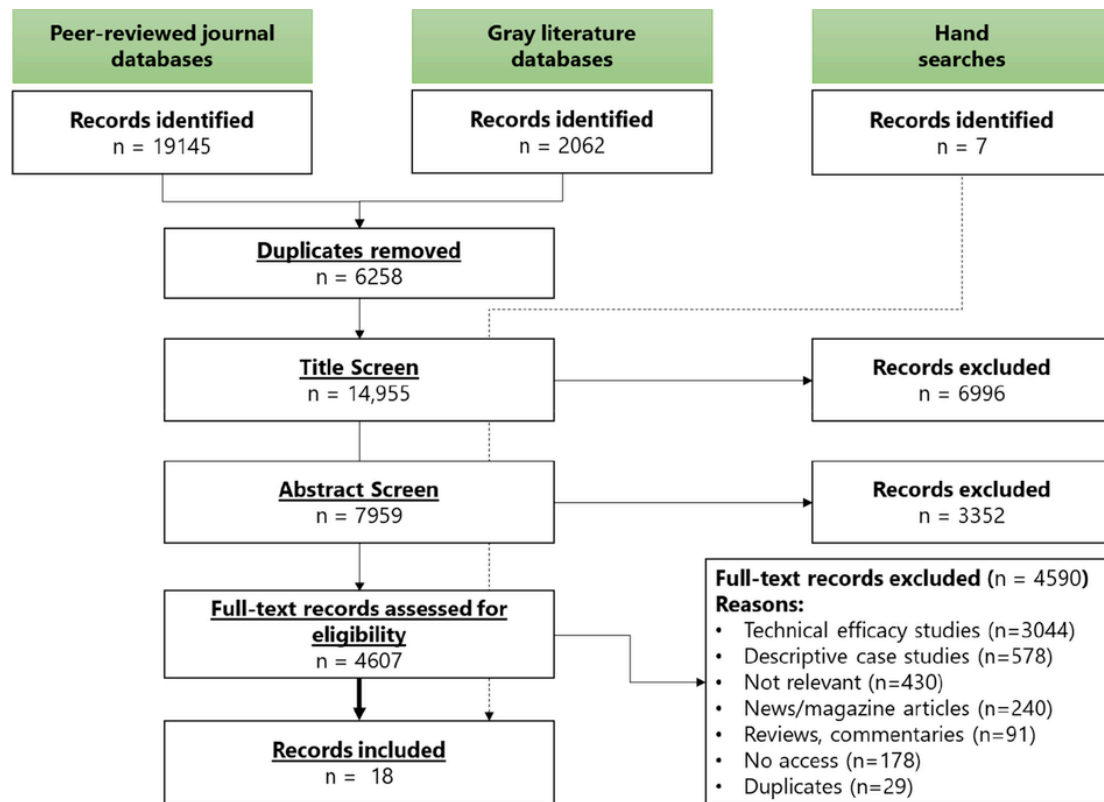


Fig. 2. Flowchart of screening and selection process of green infrastructure (GI) studies for stormwater and flood management reporting human health and social well-being outcomes (adapted from Moher et al., 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

### 3.4.2. Changes in economic well-being

Thirteen studies evaluated outcomes relating to GI for stormwater and flood management on economic well-being (Fig. 3; Table 3). The types of GI varied in scale, from green roofs for stormwater management (Ichihara and Cohen, 2011), green streets and tree canopy (Donovan and Butry, 2010; Netusil et al., 2014, 2010), urban drain restoration (Polyakov et al., 2017), greenways for preserving floodplains (Kousky and Walls, 2014), urban riparian corridors (Bark et al., 2009; Netusil, 2006), stormwater retention basins (Irwin et al., 2017), restored wetlands (Pan et al., 2011), preserved urban forests (Thorsnes, 2002), and a combination of low impact development (Tupper, 2012; Ward et al., 2008).

Ten out of 13 economic studies used a hedonic price model to analyze the relationship between GI and property value or housing rents. The hedonic method is an indirect valuation method, where the model estimates a “household’s marginal willingness to pay for changes in environmental and urban attributes,” typically using secondary data on property sales and characteristics (Parmeter and Pope, 2012; Taylor, 2003). All hedonic price studies in this review used data from local government departments or tax assessors. One study (Netusil et al., 2010) also conducted mail-in surveys about home buyers’ preferences on tree canopy characteristics. Housing prices were typically analyzed by proximity of homes to GI. One study descriptively analyzed sale prices between homes in a low impact development versus homes in three traditional housing developments (Tupper, 2012).

Results from the property value studies varied, but most reported that proximity to GI was associated with higher residential property values. Estimated increases in house sale price ranged from 0.75% to 2.52% in a tree canopy cover study (Netusil et al., 2010) to 19%–35% in a suburban forest preserve study (Thorsnes, 2002). Tupper (2012) reported that, although low impact development infrastructure costs

were on average 34% higher (\$30,109) than traditional development (\$19,740), houses in the former were able to retain sale price value better than traditional developments in the aftermath of the 2007 recession (13.9% decrease in low impact development area vs. 18.3%–48% in traditional areas). Polyakov et al. (2017) reported an initial negative effect on house prices at the beginning of a restoration project due to the initial dis-amenity brought on by construction activities but reported an increase in home value within four years. On the other hand, Irwin et al. (2017) reported that proximity to a conventional stormwater basin lowered property values by 13–14% (\$28,185–30,579), controlling for other factors. Several studies also emphasized that benefits were highly localized (Thorsnes, 2002). All studies used retrospective cross-sectional data; therefore, while the statistical associations they report provide information on the relationships between GI and property values, they do not indicate causality.

Only one study attempted to measure livelihood outcomes (improved income, increased well-being, reduced vulnerability, sustainable use of natural resource base) as a result of GI for flood management. Pan et al. (2011) conducted nine rounds of cross-sectional surveys with three groups of displaced farmers in China near a restored wetland, reporting improvements in household income, well-being, reduced vulnerability to food shortage, and more sustainable use of the natural resource base near the GI. However, these outcomes were not disaggregated by farmer group.

### 3.4.3. Changes in flood resilience and social acceptance of GI

We did not identify any studies that measured changes in knowledge or perceptions of flood risk or resilience as a result of GI programs (Fig. 3). We included five studies that reported changes in knowledge about GI functions, benefits, or perceptions, such as a change in the desire to install GI. Three studies, all from Portland, Oregon, used different study designs to measure the influence of GI projects on people’s

**Table 2**

Characteristics of studies about green infrastructure (GI) for stormwater and flood management and human health and social well-being (n = 18).

| Variables                                                                                  | No.<br>(%)  |
|--------------------------------------------------------------------------------------------|-------------|
| <b>Study location</b>                                                                      |             |
| USA, Pacific Northwest                                                                     | 8<br>(44%)  |
| USA, Northeast, Southeast                                                                  | 4<br>(22%)  |
| USA, Midwest                                                                               | 2<br>(11%)  |
| USA, West                                                                                  | 1 (6%)      |
| Australia                                                                                  | 2<br>(11%)  |
| China                                                                                      | 1 (6%)      |
| <b>Setting</b>                                                                             |             |
| Urban/sub-urban                                                                            | 16<br>(89%) |
| Rural                                                                                      | 1 (6%)      |
| Natural                                                                                    | 1 (6%)      |
| <b>Study design</b>                                                                        |             |
| Cross-sectional                                                                            | 14<br>(78%) |
| Pre-post                                                                                   | 3<br>(17%)  |
| Longitudinal, repeated cross-sections                                                      | 1 (6%)      |
| Experimental                                                                               | 0 (0%)      |
| <b>Data collection type</b>                                                                |             |
| Secondary data sources                                                                     | 11<br>(61%) |
| Primary social or health data sources                                                      | 6<br>(33%)  |
| Both                                                                                       | 1 (6%)      |
| <b>GI Type</b>                                                                             |             |
| Green streets, street trees, rain gardens, bioswales                                       | 8<br>(44%)  |
| Urban riparian corridor, greenway, drain/stream restoration                                | 4<br>(22%)  |
| Low impact development, multiple (pervious pavement, stormwater ponds, bioretention cells) | 1 (6%)      |
| Green roofs                                                                                | 1 (6%)      |
| Rain barrels                                                                               | 1 (6%)      |
| Stormwater retention basin                                                                 | 1 (6%)      |
| Preserved forest                                                                           | 1 (6%)      |
| Restored wetland                                                                           | 1 (6%)      |
| <b>Field associated with publication</b>                                                   |             |
| Economics and finance                                                                      | 6<br>(33%)  |
| Urban planning/geography                                                                   | 4<br>(22%)  |
| Ecology, natural resource management                                                       | 3<br>(17%)  |
| Water/flood research                                                                       | 3<br>(17%)  |
| Engineering and technology                                                                 | 1 (6%)      |
| Extension and outreach                                                                     | 1 (6%)      |
| <b>First author's primary affiliation</b>                                                  |             |
| Economics and finance                                                                      | 10<br>(56%) |
| Natural resources/forestry sciences/agriculture                                            | 3<br>(17%)  |
| Urban planning/geography                                                                   | 2<br>(11%)  |
| Civil and environmental engineering                                                        | 1 (6%)      |
| Environmental health                                                                       | 1 (6%)      |
| Sociology                                                                                  | 1 (6%)      |

perceptions of GI and neighborhood quality, which we include as a proxy for increased desirability or adoption of GI. Shandas (2015) used a pre-post study design to measure the effect of constructing bioswales and conducting community outreach on people's perceptions across eight treatment and control neighborhoods over two years. Neighborhoods that received informational materials and were slated to receive GI reported small but statistically significant increases in perceptions of neighborhood quality (e.g., change in attractiveness score of 0.53 on a

scale of 1–6), reflecting “high levels of anticipation” (Shandas, 2015). Although the author reported an overall positive trend in expected outcomes, the quasi-experimental study design does not permit causal inference.

The second study on perceptions more narrowly analyzed the association between “green streets” and walkability (Adkins et al., 2012). Authors created an “attractiveness for walking” score of 0–1 through a survey-based mapping exercise and physical inventories of green streets. They reported that green street facilities, which had easily visible and attractive greenery were one of the strongest predictors for perceived walkability, increasing attractiveness scores of a street segment by 0.34 (Adkins et al., 2012). The third Portland-based study on bioswales used a qualitative study design. Authors interviewed residents living near six bioswale sites installed between 2005 and 2006, 2009–2010, and 2012–2013 to test the hypothesis that people's awareness and favorable perceptions of bioswales and GI would correlate positively with the age of the bioswale. They did not observe any such trends in perceptions, noting that their study “challenges the assumption that opinions will improve over time following the construction phase, as flora develop and bioswales become more accepted. However, whether this was due to lower levels of maintenance, plant-choices, or other neighborhood factors is beyond the scope of our data” (Everett et al., 2015).

Two other studies collected primary data, but reported less detailed information on their social research methods. In a study of a price auctions to encourage private stormwater retention practices in Melbourne, Australia, Fletcher et al. (2011) reported that 64% of landholders recognized the importance of rainwater harvesting to protect urban streams (vs. 35% in control). Through pre-post surveys, they also reported an increase in residents' “awareness of their local creek and its ecological condition,” but did not provide numbers to support this assertion (Fletcher et al., 2011). Bakacs et al. (2013) surveyed participants in New Jersey and Virginia, United States, before and after a rain barrel program, and reported an increase in participants' knowledge of runoff reduction (+16-percentage point (pp), n = 236) and downspout diversion (+8-pp, n = 237). Although the study was not designed to rigorously detect changes, authors reported a statistically significant increase in those strongly agreeing that they will redirect downspouts to pervious areas (+7-pp, n = 186), and those planning to install a rain garden (+8-pp, n = 175).

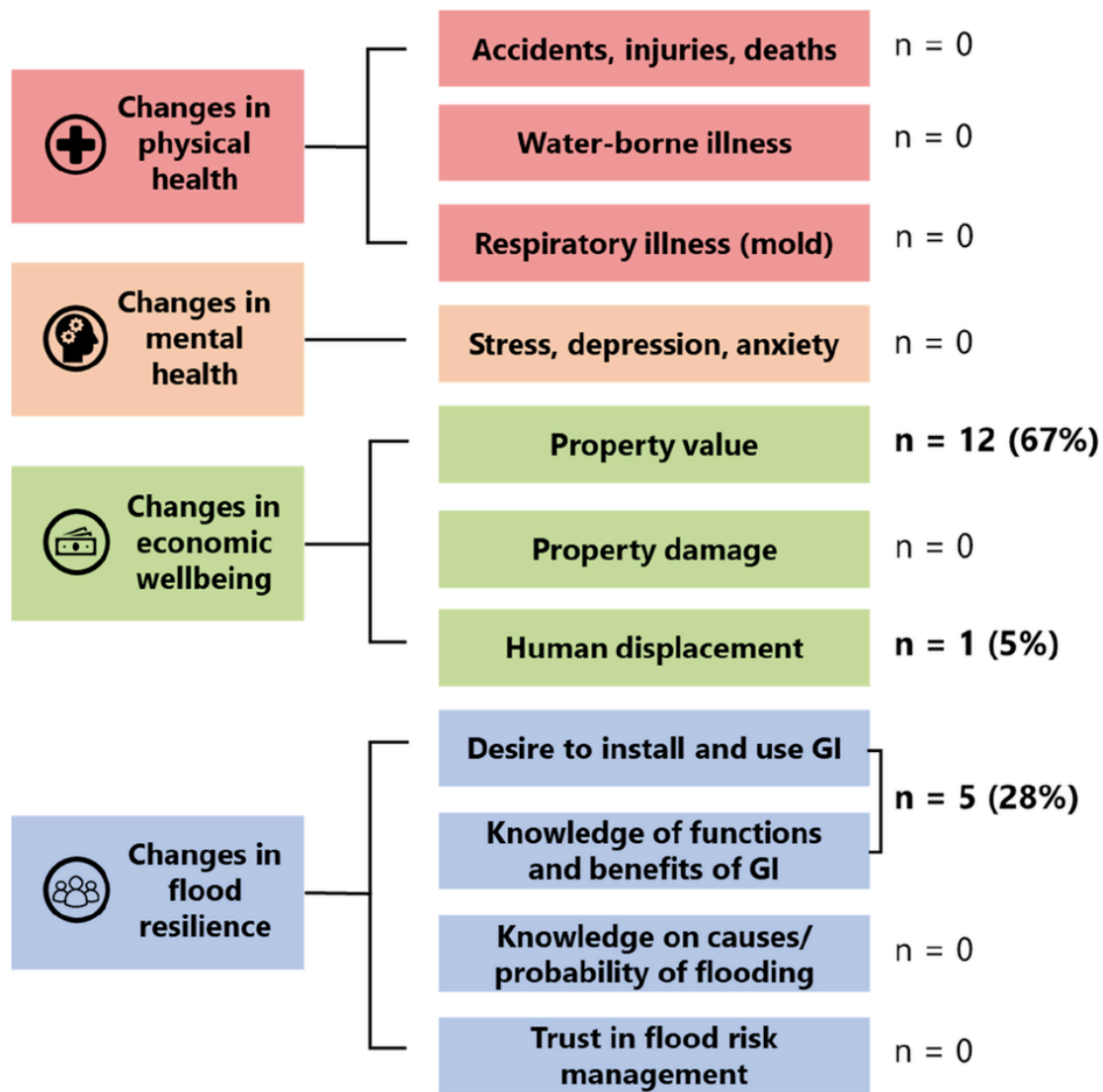
## 4. Discussion

### 4.1. The state of the evidence

Out of more than 20,000 publications we identified about GI designed for stormwater and flood management, only 18 studies directly analyzed outcomes relating to human health or social well-being. Of the 4607 papers reviewed, most (n = 3044) evaluated the technical efficacy of GI, and another 578 provided descriptive case studies of GI construction and performance. We analyze these types of studies in forthcoming review papers. Although most of the 18 studies we included were of high quality, few studies used primary survey or interview data, and none allowed for causal inference.

Literature on health outcomes from GI projects designed for stormwater and flood management was entirely absent. Studies using secondary data, such as life cycle assessments, can help estimate or project cancer, non-cancer, and respiratory health impacts at a higher scale using existing models (Flynn and Traver, 2013). However, high-resolution studies are needed to measure impacts at the individual, household, and neighborhood scale. We could use existing studies on green-space and health to fill this gap, as they provide evidence for the broader health benefits of GI (e.g. Beyer et al., 2014; Kardan et al., 2015). Indeed, there is considerable value in combining GI studies on





**Fig. 3.** Number of studies about green infrastructure (GI) for stormwater and flood management reporting outcomes relating to human health and social well-being ( $n = 18$ ). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

stormwater, heat mitigation, and air quality improvements given the interconnectedness of these themes. However, given the documented ways in which flooding on its own can affect physical and mental health (Ahern et al., 2005; Du et al., 2010; Saulnier et al., 2017), we argue that there needs to be more rigorous research that specifically explores the connection between GI projects designed to address stormwater-related flooding and relevant health impacts.

We identified five studies that measured changes in people's perceptions of GI for stormwater and flood management, but none were designed to rigorously test the impact of GI projects on knowledge, perceptions, or attitudes. The most rigorous study reported increasingly positive perceptions of neighborhood quality over a two-year period (Shandas, 2015). Nearly all the 13 studies that measured changes in economic well-being reported a positive association between GI for stormwater and flood management and property values. These findings are largely concurrent with other greenspace hedonic price studies (Jim and Chen, 2010; Moranchó, 2003; Plant et al., 2017; Poudyal et al., 2009; Rossetti and Raschky, 2013; Sander et al., 2010; Zhang et al., 2015). Other econometric methods to estimate the economic value of GI or other environmental features include the life satisfaction approach (e.g. Bertram and Rehdanz, 2015; Tsurumi and Managi, 2015); cost-benefit analyses (Dai et al., 2016; Daigneault et al., 2016; Hopton,

2015; McPherson, 1992; Raucher and Clements, 2009); and stated preference studies (see Brander and Koetse, 2011 for a meta-analysis of studies on urban open space).

While these economic valuation methods remain important and useful tools for planners to estimate the costs and benefits of proposed projects, there are myriad other ways in which GI may improve economic well-being that remain unmeasured. For example, since urban flooding can cause property damage, displace families, and reduce economic productivity (Hallegatte et al., 2013; Kennedy et al., 2008; Luechinger and Raschky, 2009; Walker and Burningham, 2011), GI designed for flood management should theoretically decrease these negative outcomes. Prior research has simulated the potential reduction in property loss due to stormwater GI projects (Kousky et al., 2013; Kousky and Walls, 2014), but we did not find any such studies using primary data. Direct observations of projects will help generate evidence on various physical and mental health, economic well-being, and flood resilience outcomes that are typically left unmeasured (Figs. 1 and 3). Such studies can provide greater context and evidence to practitioners and policymakers alike, particularly as municipalities, states, and countries integrate GI into their climate action plans (e.g. City of Chicago, 2008; Government of India, 2008).

**Table 3**

Summary of included studies about green infrastructure (GI) for stormwater and flood management and human health and social well-being (n = 18).

| Quality Appraisal                                                     | Reference                 | Study design                    | Data source(s)                                         | Analytical method                 | Data collection year(s)          | Setting        | Location                                 | GI Type                                                 | Sample size                                              |
|-----------------------------------------------------------------------|---------------------------|---------------------------------|--------------------------------------------------------|-----------------------------------|----------------------------------|----------------|------------------------------------------|---------------------------------------------------------|----------------------------------------------------------|
| <b>Studies relating to social acceptance of GI (flood resilience)</b> |                           |                                 |                                                        |                                   |                                  |                |                                          |                                                         |                                                          |
| High                                                                  | Adkins et al. (2012)      | Cross-sectional                 | Surveys, inventory (P)                                 | Ordinary least squares regression | 2006–2008                        | Urban/suburban | Portland, Oregon, USA                    | Vegetated catchment basins                              | n = 748 homes<br>n = 321 roadways<br>n = 237 individuals |
| Medium                                                                | Bakacs et al. (2013)      | Pre-post                        | Surveys (P)                                            | Difference in means               | 2010–2011                        | Urban/suburban | New Jersey and Virginia, USA             | Rain barrels                                            | n = 237 individuals                                      |
| High                                                                  | Everett et al. (2015)     | Cross-sectional                 | Interviews (P); GI database (S)                        | Qualitative thematic analysis     | Not stated                       | Urban/suburban | Portland, Oregon, USA                    | Bioswales                                               | n = 45 individuals                                       |
| Medium                                                                | Fletcher et al. (2011)    | Pre-post                        | Surveys (P)                                            | Not stated                        | Not stated                       | Urban/suburban | Melbourne, Australia                     | Rainwater tanks, raingardens, downpipe diversions       | Not stated                                               |
| High                                                                  | Shandas (2015)            | Pre-post, quasi-experimental    | Surveys (P)                                            | Difference in means               | 2009–2011                        | Urban/suburban | Portland, Oregon, USA                    | Vegetated stormwater facilities, trees                  | n = 132 homes                                            |
| <b>Studies relating to economic well-being</b>                        |                           |                                 |                                                        |                                   |                                  |                |                                          |                                                         |                                                          |
| High                                                                  | Bark (2009)               | Cross-sectional, retrospective  | Sale prices, satellite data (S); Ecological survey (P) | Hedonic price model               | 1998–2003                        | Urban/suburban | Tucson, Arizona, USA                     | Urban riparian corridor                                 | n = 978 home sales                                       |
| High                                                                  | Donovan and Butry (2010)  | Cross-sectional, retrospective  | Sale prices, satellite data (S); Observations (P)      | Hedonic price model               | 2006–2007                        | Urban/suburban | Portland, Oregon, USA                    | Street trees                                            | n = 2608 home sales                                      |
| Medium                                                                | Ichihara and Cohen (2011) | Cross-sectional, retrospective  | US census, rental price data, satellite data (S)       | Hedonic price model               | Census: 2000; Rent: "late 2000s" | Urban          | New York City, New York, USA             | Green roofs                                             | n = 44 apartments                                        |
| High                                                                  | Irwin et al. (2017)       | Cross-sectional, retrospective  | Sale prices, satellite data, stormwater basin data (S) | Hedonic price model               | 1996–2007                        | Suburban       | Baltimore, Maryland, USA                 | Stormwater retention basin                              | n = >90,000 home sales                                   |
| High                                                                  | Kousky and Walls (2014)   | Cross-sectional, retrospective  | Sale prices, satellite data (S)                        | Hedonic price model               | 2008–2012                        | Natural        | Southern St. Louis County, Missouri, USA | Greenway: floodplain preservation                       | n = 36,000 "residential parcels"                         |
| Medium                                                                | Netusil (2006)            | Cross-sectional, retrospective  | Sale prices (S)                                        | Hedonic price model               | 1999–2001                        | Urban/suburban | Portland, Oregon, USA                    | Restored riparian corridor                              | n = 1665 home sales                                      |
| High                                                                  | Netusil (2010)            | Cross-sectional, retrospective  | Surveys (P); sale prices, satellite data (S)           | Hedonic price model               | 1999–2001                        | Urban/suburban | Portland, Oregon, USA                    | Tree canopy cover                                       | n = 440 individuals<br>n = 30,015 home sales             |
| High                                                                  | Netusil et al. (2014)     | Cross-sectional, retrospective  | Sale prices, satellite data (S); vegetation cover (P)  | Hedonic price model               | 2005–2007                        | Urban/suburban | Portland, Oregon, USA                    | Green streets                                           | n = 29,712 home sales                                    |
| Low                                                                   | Pan et al. (2011)         | Repeated cross-sections         | Surveys, interviews (P)                                | Descriptive statistics            | 2000–2008                        | Rural          | Xipanshanzho, Dongting Lake, China       | Restored wetland                                        | n = 1683 individuals                                     |
| High                                                                  | Polyakov et al. (2017)    | Unbalanced panel, retrospective | Sale prices (S)                                        | Hedonic price model               | 1990–2013                        | Suburban       | Perth, Australia                         | Urban drain restoration                                 | n = 339 home sales                                       |
| High                                                                  | Thorsnes (2002)           | Cross-sectional, retrospective  | Sale prices (S)                                        | Hedonic price model               | 1989–2000                        | Suburban       | Grand Rapids Michigan, USA               | Preserved forest                                        | n = 421 lot sales<br>n = 486 home sales                  |
| Medium                                                                | Tupper (2012)             | Cross-sectional, retrospective  | Sale prices; infrastructure costs (S)                  | Descriptive statistics            | 2006–2011                        | Suburban       | South Carolina, USA                      | Pervious pavement, stormwater ponds, bioretention cells | n = 239 home sales                                       |
| High                                                                  | Ward (2008)               | Cross-sectional, retrospective  | Sale prices (S)                                        | Hedonic price model               | 2005–2008                        | Urban/suburban | Seattle, Washington, USA                 | Bioswales, vegetation                                   | n = 4970 home sales                                      |

**Notes.**1. Quality Appraisal: High (score of  $\geq 10$  to 14); Medium (score  $\geq 5$  and  $< 10$ ); Low (score  $< 5$ ).

2. Data source(s) column: (P) = primary data; (S) = secondary data.

By documenting rigorous evidence on each of these health and well-being outcomes, we can begin to better understand their interconnectedness, which can inform multi-pronged interventions. This will also enable us to link human health to ecosystem health and explore feedback loops between the human and natural systems. Given the in-

creasing body of research on coupled human-and-natural systems (CHANS), there is a need to improve the rigor of social and human health measures to provide better inputs into these frameworks (Kline et al., 2017; Kramer et al., 2017).



## 4.2. Recommendations

Based upon findings from this review, we suggest four main changes to how GI programs are evaluated.

**1. First, there is a critical need to generate evidence on health and social well-being outcomes relating to GI for stormwater and flood management.** While many studies note in passing that there are health, social, cultural, and aesthetic co-benefits, this systematic review makes it clear there is little documented evidence (Chang et al., 2018; Chenoweth et al., 2018; Grimmond, 2007; Hopton, 2015; Rogers, 2013). Similar shortcomings were noted in a review of 84 ecosystem services frameworks, which found that 75% did not include “feedback mechanisms between ecosystems and human health” (Ford et al., 2015).

Furthermore, much of the ecosystem services literature is focused on economic valuation of services, which has been criticized by others; for example, Martín-López et al. (2014) argue that this approach does not adequately reflect the “concerns of their beneficiaries” and biases results to only information that is able to be monetized. As a result, claims of co-benefits for health and social well-being—albeit logical—remain unsubstantiated. Furthermore, a systematic review reported limited evidence of the use of economic valuation of ecosystem services by policymakers (Laurans et al., 2013). While this could be due to ineffective dissemination of study findings, it also indicates an opportunity to provide policymakers with alternative metrics of health and social well-being relating to GI for stormwater and flood management to help fill an important knowledge gap and inform their decisions. It would enable planners, engineers, and conservation advocates to comprehensively identify benefits in different conditions and contexts for effective adoption of GI in infrastructure design and urban planning, particularly in the context of climate change.

**2. Second, there is a need for more context-specific social and health research from a wider range of locations, particularly from cities in South and Southeast Asia, Latin America, and Sub-Saharan Africa.** Most studies we identified that measured changes in health or social well-being outcomes were concentrated in the city of Portland, Oregon, with a few examples from other cities in the United States, Australia, and China. This considerable geographical bias is problematic because GI for stormwater and flood management is of global relevance, and will require context-specific implementation and evaluation (Schifman et al., 2017; Votsis, 2017). We suggest that the incorporation of GI is more critical in rapidly-urbanizing flood-prone cities and towns in lower- and middle-income countries with inadequate drainage systems, which are simultaneously more vulnerable to the effects of climate change (Chatterjee, 2010; Huang et al., 2018; Li et al., 2017; Mguni et al., 2015; Ranger et al., 2011; Thanvisitthpon et al., 2018). In such contexts, large-scale gray infrastructure development is less widespread, potentially motivating these cities to adopt a more cost-effective and sustainable combination of green and gray infrastructure into their climate action plans.

**3. Third, research on GI for stormwater and flood management must incorporate a program evaluation approach** (Rossi et al., 2003). We have suggested options and potential uses of various methods to facilitate program evaluation (Table 4). This perspective is critical to measure and attribute changes in outcomes to a GI project, using baseline (pre-intervention) measurements of a population or an outcome of interest, and comparing them to different time points. Most studies we found used secondary data or modeled hypothetical scenarios. To be able to specifically attribute outcomes to

GI projects, direct field studies will be required that incorporate rigorous evaluation design and epidemiological techniques. Relevant designs include randomized controlled trials where investigators assign otherwise similar groups to the exposure (GI) or control (no GI) (e.g. Mäusezahl et al., 2009), “natural experiments” that leverage already-occurring exposure-control phenomena (e.g. Wu and Malaluan, 2008) and quasi-experimental designs, where matched comparison groups can be surveyed (e.g. Shandas, 2015). Attribution can also be achieved by incorporating statistical techniques such as propensity score matching and difference-in-difference estimators (Ferdinand et al., 2016; Lechner, 2011). Indeed, Parmeter and Pope (2012) note that even traditional hedonic price studies can incorporate quasi-experimental study designs (for examples in the context of flood risk, see Carbone et al., 2006; Hallstrom and Smith, 2005; Pope, 2008). However, none of the hedonic price studies relating to GI used these designs. Finally, qualitative studies can complement quantitative studies by documenting the implementation process and uncovering contextual factors that enable or constrain the effectiveness of GI projects (see Table 4 for examples of research questions and methods).

**4. Fourth, we echo and highlight the calls of other researchers for interdisciplinary investigations of GI** (Frumkin et al., 2017; Gordon et al., 2018; Jackson, 2003; Shandas, 2015; Wolf et al., 2015). Only a handful of the authors in the 18 included studies have a background in the social sciences (Table 2). The inclusion of social scientists and public health researchers in studies of the impacts of GI for stormwater and flood management would facilitate a more holistic evaluation. These fields can add considerable value to the study of GI using well-established quantitative and qualitative methods (see Table 3 with suggested best practices), including surveys, interviews, and focus group discussions with a range of involved stakeholders, and using participatory approaches including community mapping and ethnographic techniques such as photo elicitation (Brown and Fagerholm, 2015; Wang, 1999). Qualitative approaches are particularly useful to understand the richness of people's lived experiences and are complementary to quantitative approaches that help provide more generalizable evidence. Without an understanding of how people interact with GI and benefit from or are impeded by it, we cannot understand the full range of benefits and outcomes from stormwater GI projects.

Our review is not without its limitations. Although we conducted a rigorous systematic search, it is possible that we may have missed some pertinent studies. This is particularly possible given the many definitions and terms for GI, and that one GI project may provide multiple benefits that are not all described in a study (e.g. GI primarily designed to reduce the urban heat island effect might not mention co-benefits for flooding or stormwater, thereby excluded from our search). Our findings are also primarily of urban significance, even though we include two non-urban studies. Our limited geographical representation may also reflect a publication bias. For example, we did not find any quantitative social research on China's “sponge city” initiatives. However, we believe that this is more indicative of gaps in research and not search limitations, because we did identify several descriptive “sponge city” case studies that did not meet our inclusion criteria of measuring outcomes on health and social well-being. We also found that most GI literature is concentrated in settings with strong policy initiatives or government funding, which suggests more of an implementation gap than publication bias.

## 5. Conclusions

Green infrastructure is more than just the sum of its technological and hydrological performance; indeed, Young et al. (2014) argue that

**Table 4**

Best practices for using mixed methods in social research to measure human health and social well-being resulting from green infrastructure (GI) for stormwater and flood management.

| Data collection methods                                                                                   | Potential uses                                                                                             | Relevant research questions (examples)                                                                                                                 | Types of participants                                                        | Typical components                                                                                                                                  | Study design options (examples)                                                                                                                                                                                                                                                           |
|-----------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Quantitative:</i><br>Surveys<br>See Fowler (2014) for guidance.                                        | Detect measurable changes in outcomes of interest at different time points (before/during/after)           | What impact did the GI project have on people's<br>- respiratory and mental health status?<br>- knowledge of GI functions?                             | People affected directly by GI                                               | - Close-ended questions<br>- Scales<br>- Standardized tests (e.g. knowledge about flood risk)                                                       | - Experimental or quasi-experimental study design<br>- Surveys of randomly sampled homeowners on health status, socio-economics, knowledge and perceptions before, during, and after GI project.<br>- Matched comparison group surveyed without GI project.                               |
| <i>Qualitative:</i> In-depth interviews<br>See Morris (2015) for guidance.                                | Document changes in perceptions, knowledge, and experiences with human dimensions of GI                    | - How did people's perceptions of health effects evolve during the GI project?<br>- What lessons were learned about GI implementation and maintenance? | - Homeowners<br>- General public<br>- City officials<br>- Private developers | - Semi-structured, open-ended questions with prompts<br>- Participatory activities, e.g. photo elicitation <sup>a</sup>                             | Interviews with homeowners, experts, policymakers, as part of:<br>- Exploratory phase: inform survey design using social and policy context<br>- During implementation of GI project: document process and perceptions<br>- Post-implementation: document experiences and lessons learned |
| <i>Qualitative:</i><br>Focus group discussions<br>See Morgan (2018) for guidance.                         | Document changes at the group level in perceptions, knowledge, and experiences with human dimensions of GI | - How did perceptions about GI and property values change after GI project?                                                                            | Groups of:<br>- Homeowners<br>- City officials<br>- Private developers       | - Open-ended questions<br>- Participatory activities, e.g. Participatory GIS (PGIS), photo elicitation, pile sorting/ranking exercises <sup>a</sup> | - Discussions before, during, and after project to document expectations, process, and perceived changes.<br>- Topics ideally pertain to group dynamics where individual perspectives are less likely to be influenced by others                                                          |
| <i>Quantitative or Qualitative:</i><br>Participant observation<br>See Emerson et al. (2011) for guidance. | Observe and detect changes in day-to-day behavior or a phenomenon                                          | - How often and in what ways do residents use green streets?<br>- How does this compare to the area before the GI project?                             | - Homeowners<br>- General public                                             | - Structured checklists<br>- Unstructured, with extensive field notes                                                                               | - Incorporated into surveys with structured checklist on status/maintenance of GI<br>- Standalone form of data collection to understand GI use                                                                                                                                            |

**Notes.**

This table is intended to provide an overview of the utility of mixed methods for measuring changes in health and social well-being outcomes. The data collection tools listed above can also be used as stand-alone, cross-sectional methods to illustrate case studies of GI projects.

<sup>a</sup> For PGIS see Dunn (2007), for photo elicitation see Wang (1999), for pile sorting see West et al. (2016).

"GI is only infrastructure through its ability to deliver goods and services." For effective application in real-world settings, GI will require widespread acceptance and maintenance of facilities to reduce flooding and improve ecological and human well-being. The limited social research and evaluation demonstrated by this review reflects an opportunity to conduct more socially relevant and geographically representative studies to better relate GI design to tangible outcomes. An interdisciplinary approach that leverages program evaluation expertise from the social sciences and public health can demonstrate the health and social well-being outcomes of GI projects. By helping understand if projects successfully mitigate the impacts of stormwater-related urban flooding on built infrastructure *and* people, as well as *why* the projects were successful, we can improve the design of GI in a way that ensures sustained and effective use in a wide array of contexts. Availability of rigorous evaluation data will ultimately improve decision-making by enabling assessment of the full range of benefits of GI relative to financing and implementation of various GI options, especially in highly urbanized, flood-prone settings around the world susceptible to the effects of climate change.

**Declarations of interest**

None.

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**Appendix A. Supplementary data**

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2019.05.028>.

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