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Developing key sustainability indicators for assessing green infrastructure performance

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Abstract

In recent years, integrated networks of green spaces at city scale, or "green infrastructure" (GI), are seen increasingly as fundamental to the delivery of ecosystem services for human and environmental health. A range of models that assess the performance of specific aspects and elements related to GI have been developed in response. However, there is no model that is comprehensive and integrative across all types of GI and ecosystem services. This paper aims to suggest a set of potential indicators that facilitate the development of an inclusive model for the sustainability assessment of GI performance.
This research is based on the findings from a previous study conducted by the authors that identified definitions, types and conceptual framework of GI as well as thirty performance indicators through reviewing literature and incorporating results from semi-structured interviews involving twenty-one selected Australian representative experts. This analysis was combined with input from 373 national and international stakeholders through an online questionnaire to establish an integrated framework by weighting, screening and aggregating selected indicators. This framework comprises a reduced set of sixteen potential indicators based on experts' perspectives which represent the key interactions between human health, ecosystem services and ecosystem health across four dimensions (ecological, economic, socio-cultural and health). Future research will involve testing this proposed framework and providing a platform for decision-makers to test various scenarios based on the base case and existing conditions to provide an early warning of changes in the sustainability levels in the urban environment.

Keywords: green infrastructure; sustainabile development; performance indicators; ecosystem services, human health, ecosystem health.

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1. Introduction

It is crucial to assess and monitor the sustainability level of built and natural environments as a result of accelerated urbanisation and global land alteration, transformation and fragmentation by humans. Accordingly, many approaches to sustainability-oriented frameworks at the project and policy level have been developed by considering the social, economic and ecological dimensions individually, and then attempting to assess and integrate these findings. The major challenges for sustainability assessment are related to the need to identify both science-based and policy-based indicators, which are able to justify a boundary between what contributes to a sustainable development and what does not. In this context, green infrastructure is identified as an alternative nature-based and cost-effective infrastructure solution for improving the sustainability of urban development [1-6]. GI is defined as an integrated network of natural and semi-natural areas and features which deliver a variety of benefits to humans and ecosystems [2, 7]. In this study, understanding the environmental performance of GI as well as the social and economic benefits has motivated the development of an indicator-based framework for assessing the sustainability performance of GI projects. To initiate the research, semi-structured interviews were conducted with 21 Australian representative experts. Results revealed nine key concepts that cover GI performance that were consistent across all interviews [8].

These nine concepts were taken as the basis to establish the assessment framework and identify suitable GI performance indicators:

1. Climate change adaptation and mitigation;
2. Human health and well-being;
3. Healthy ecosystem;
4. Biodiversity;
5. Economic benefits;
6. Alignment with political issues and city strategies;
7. An active travel network;
8. Water management;
9. Food production.

Most of the common sustainability and environmental frameworks for selecting indicators were developed based on the causal network (CN) method [9] such as pressure-state-response (PSR), force-state-response (DSR) and force-pressure-state-impact-response (DPSIR). By reviewing the literature and the results from the semi-structured interviews, Pakzad and Osmond [10] proposed a set of 30 GI performance indicators based on DPSIR. This indicator set focuses on the key interactions between human health, ecosystem services and ecosystem health, which is in line with proposed frameworks by other scholars [1, 4, 11, 12]. This framework helps to clarify the complex relationship between cause and effect variables, to understand the issues that change the performance of GI and to identify potential solutions [10]. However, a quantitative approach was required to verify and validate the findings that resulted from the qualitative research phase (semi-structured interviews) and to test the conceptual framework and the 30 GI performance indicators proposed in the previous study.

2. Methodology

2.1. Target Population

The questionnaire was emailed to 1387 individuals, who were selected because they were national and international experts in the field of built environment and/or sustainability. Out of the potential 1387 respondents, 1152 had valid email addresses. The information issued to the respondents included a URL link to an online questionnaire. This information was also distributed to the mailing lists of participant organizations, which were identified in the first round of semi-structured interviews. Additionally, the questionnaire invitation was distributed on the news web page of representative organizations such as Australian Institute of Landscape Architects, Australian Institute of Architects, Low Carbon Living CRC, Infrastructure Sustainability Council of Australia, Australian Sustainable Built Environment Council and the United Habitat. In statistical terms, the population size in this study was ‘infinite’ because the total number of people who are experts in the field of sustainability, rating tools and GI nationally and internationally is unknown.

2.2. Sample Size

As indicated by Babbie [13] and Creswell [14], sampling is necessary because time constraints make it impossible to study whole populations. Two non-probability sampling techniques were utilised for this study: expert sampling and snowball sampling.

Based on the ‘correction infinite sample size population formulas’ suggested by Godden [15], the survey would require a minimum sample size of 289 participants to be representative of the target population to achieve a confidence interval of 95% with a margin of error of ± 5%. In the event, the questionnaire attracted 373 respondents.

2.3. Questionnaire Design

The questionnaire provided for this study consisted of open and closed-ended questions asking the respondents to choose among various statements that are closest to their own attitude and concerns. A Likert scale was used to present clear positive or negative choices, to which the respondent was asked to indicate agreement on a scale from ‘strongly agree’ to ‘strongly disagree’[16]. According to the general rules of a well-constructed survey questionnaire, it must consist of several hierarchical layouts/sections with corresponding objectives for each section. In this case the questionnaire contained three sections, including 26 specific questions and 60 sub-questions:

- Section A included seven questions aimed at verifying GI definitions and framework.
- Section B included nine main questions with the aim of rating GI performance indicators and selecting the key indicators from among the entire list of indicators.
- Section C comprised ten questions aimed at determining participants’ knowledge and experience.

2.4. Piloting

The questionnaire was pilot tested with five individual experts. They tested the feasibility and the validity of all questions and the time it took to complete the questionnaire. Minor changes were made to the research questions, which included:

- less paraphrasing and more detailed explanations to eliminate potential ambiguity;
- shifting the demographic and personal information to section C;
- changing the five-point Likert scale to a three-point Likert scale in Section A to rate the proposed definitions and frameworks obtained from semi-structured interviews and literature review, and
- changing the three-point Likert scale to a five-point Likert scale in Section B for weighting indicators. The reason for this was to obtain clear weightings for all indicators and to help identify the most relevant and key indicators.

3. Summary of Findings

The data from the questionnaire was analysed using SPSS 22 (Statistical Package for the Social Sciences). Each question was coded based on a three-point Likert scale (for Section A responses) and a five-point Likert scale (for Section B responses).

3.1. Participants’ Profile

Out of the 373 completed questionnaires, 241 participants were from across all states of Australia, with a majority from New South Wales (107 participants), and Victoria, (58). The majority of international respondents were from Europe (36.5%) with North America a close second (28%).

In relation to the expertise and background of the respondents, 145 (35.63%) are/were practitioners, 167 (41.03%) are academics, and 95 (23.34%) are from state and local government agencies.

As shown in Fig. 1, the majority of experts are landscape architects, urban planners, architects and ecologists and are involved equally in design/planning and research fields. In addition, 60% of the participants have more than 10 years' work experience, which indicates the high quality level of data collected.

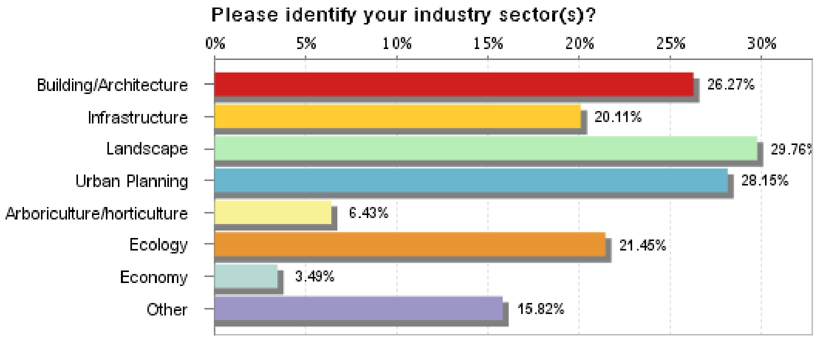

Fig. 1 Participants' industry sectors.

As illustrated in Fig. 2, the majority of the experts (175 or 46.92%) have been involved in the field of Climate Change and Water Management (159 or 42.63%), Ecology (154 or 41.29%), Energy (149 or 39.95%) and Health and Well-being (114 or 30.56%).

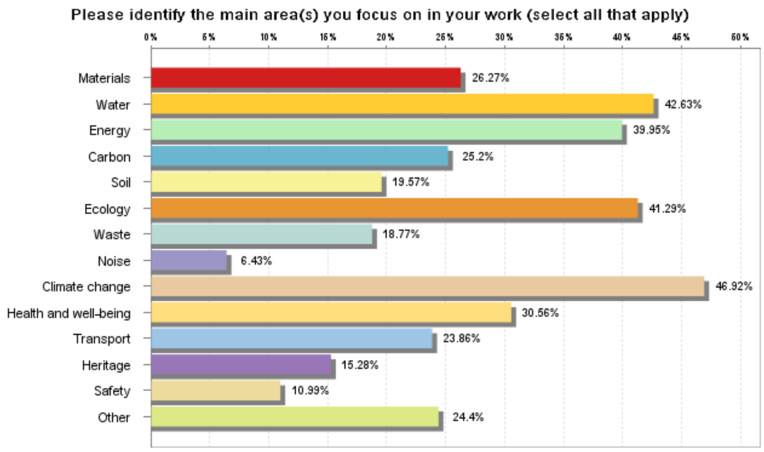

Fig. 2 Participants' specific field and focus area.

3.2. Definition and framework of GI (section A)

In Section A of the questionnaire, the respondents were asked to provide 'Yes' or 'No' answers to three questions. The questions were focused on identifying the backgrounds of the participants and the familiarity they had with the three concepts of: GI Planning, Triple Bottom Line (TBL) of Sustainability, and the Millennium Ecosystem (service) Assessment framework (MEA). It was found that 359 (96.25%) of the 373 experts are familiar with the term 'Green Infrastructure'. 287 (76.94%) are familiar with the concept of 'TBL of Sustainability' and only 131 (35.12%) are aware of the MEA framework.

It is worthwhile to mention that 142 (38.07%) out of 373 participants in Australia and internationally have been involved directly in the development of sustainability assessment tools, models and frameworks through the contribution of their knowledge to programs or by assisting in the validation of tools.

Four definitions were identified from the semi-structured interviews in our previous study [8]. Then, respondents were asked to note their levels of agreement with these four proposed definitions using a three-point Likert scale.

The four definitions are:

Definition 1: GI is a policy and strategic approach to land and species conservation.

Definition 2: GI is a network of energy, materials and species flows that maintains and improves ecological functions in combination with multifunctional land uses and provides associated benefits to human populations and ecosystems.

Definition 3: GI refers to the integration of ecological functions through natural and engineered networks into conventional infrastructure systems to enhance their functions, and it can significantly reduce their carbon footprint.

Definition 4: GI is an ecological solution underpinned by the concept of ecosystem services to improve the sustainability level of the urban and built environment. It embraces the idea of the Triple Bottom Line – the social, economic and environmental aspects of the urban environment.

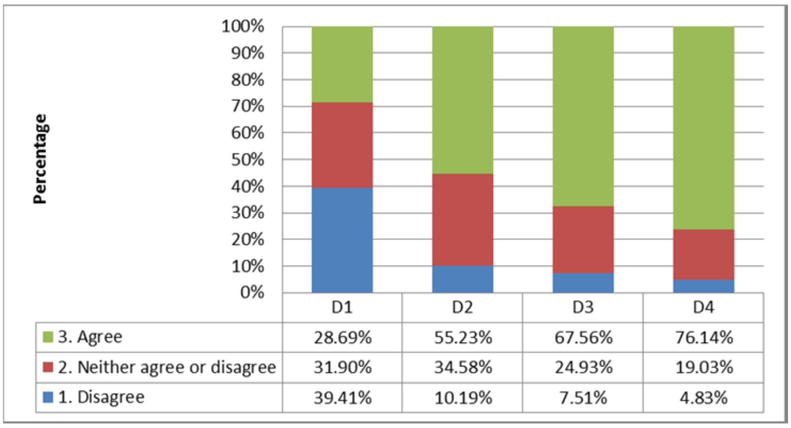

Fig. 3 Green infrastructure definitions.

Fig. 3 illustrates that most respondents agreed with Definitions 2, 3 and 4, with an agreement percentage of 52.23% (206) for D2, 67.56% (252) for D3 and 76.14% (284) for D4. In contrast, 39.41% (147) of participants disagree with the first definition. The overall results for this question indicate that the fourth followed by the third definition implied the best description of GI. This is aligned with the results from the semi-structured interviews with 21 Australian experts, in which the fourth definition was the most approved definition [8].

Three assessment frameworks were tested by Pakzad and Osmond [8] through interviews. Accordingly, a set of hypotheses were utilised for each proposed framework and participants were asked to determine the level of their agreement with these three hypotheses, as follows:

HaF1: The TBL Sustainability Framework (Environmental, Social and Economic) can be an appropriate framework for measuring GI performance.

HaF2: The Millennium Ecosystem Assessment framework (Provisioning services, Regulating services, Cultural services and Supporting services + Biodiversity) can be an appropriate framework for measuring GI performance.

HaF3: A combination of both frameworks (TBL and MEA) can be an appropriate framework for measuring GI performance.

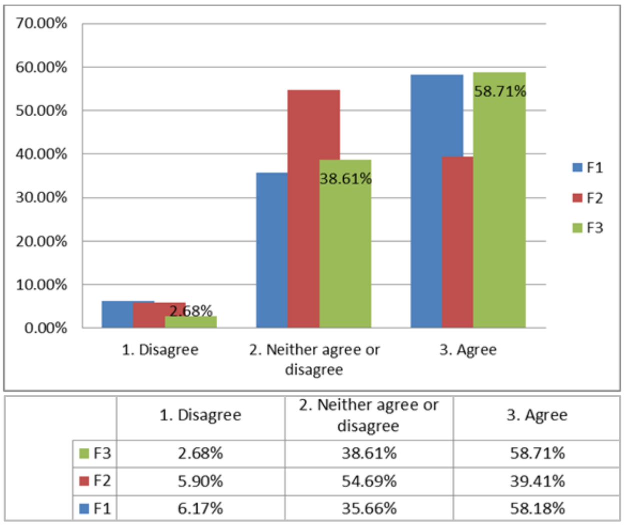

Fig. 4 Identifying the appropriate framework.

Analysing the results illustrates that the third framework (Combination of TBL and MEA) followed by the first framework (TBL) achieved the highest scores (Fig. 4); results from the earlier semi-structured interviews indicated a similar outcome.

The respondents then were asked to rate the degree of importance of sub-categories of MEA and TBL separately by using a five-point Likert scale. Table 1 presents the results for weighting and ranking the subcategories of the MEA framework. ‘Regulating services’ scored the highest. However, all 4 subcategories, with only minor differences, (1-2%), achieved similar levels of importance. The ‘Environmental’ subcategory also achieved the highest score in the TBL framework (Table 2).

Table 1. Weighting subcategories of MEA framework.

Provisioning services	Regulating services	Cultural/social services	Supporting services
24.96%	26.76%	23.15%	25.13%

Table 2. Weighting subcategories of TBL framework.

Environmental	Social cultural	Economic
36.72%	32.71%	30.57%

3.3. Analysis to identify the important indicators in measuring the level of sustainability (Section B)

At this stage, the initial set of indicators was classified into four main categories: Ecological indicators; Human health indicators; Socio-cultural indicators and Economic indicators. Then, each participant was given 100 points to distribute over these four subcategories. This approach is the Budget Allocation (BAL). The main advantage of BAL is its transparency and relatively straightforward approach to getting stakeholders’ opinions on each indicator [17]. Table 3 presents the average assigned weight of BAL for each category.

Table 3. Weighting main categories.

GI performance assessment framework	Mean	Number of indicators
Ecological indicators (ecosystem health)	32.43%	9
Human health indicators	25.91%	3
Socio-cultural indicators	20.86%	8
Economic indicators	20.80%	10

In the second stage, each participant was asked to score the importance of each indicator in terms of its contribution to sustainability assessment using a five-point Likert scale.

A descriptive analysis and Cronbach's alpha reliability test were conducted to identify the central tendencies of the data. The Cronbach's alpha result (α=0.929) was higher than the accepted reliability threshold stated by George and Mallery [18].

Afterwards, exploratory analysis was undertaken to evaluate the importance of each indicator within the above four categories and determine the level of agreement among participants by applying the Weighted Average Index method [16, 19]. The reason for using the WAI is to identify and select key performance indicators with the highest level of contribution in the assessment model by relying on expert judgment.

The WAI for each indicator was calculated by adding up the response numbers for each indicator multiplied by a weighted value between 0.2 and 1 and dividing the sum by the number of total responses. This provides an overall weighted average score for each particular indicator.

$$WAI = \frac{\sum f_i w_i}{\sum f_i}$$

fi= frequency of the respondents
wi= The weight of each of the Likert score values assigned as follows:

Not Important (1)	0.2
Slightly Important (2)	0.4
Moderately Important (3)	0.6
Important (4)	0.8
Very Important (5)	1

An example of WAI calculation for the climate and microclimate modifications indicator:

*WAI= (2*0.2+4*0.4+39*0.6+130*0.8+198*1)/373= 0.878*

As listed in Table 4, the mean response rating value for the 30 performance indicators offered to respondents' ranges from a maximum of 4.53 (improving physical well-being) to a minimum of 3.23 (noise level attenuation). No indicator mean value score fell under the 'not important' value (or <1.5). In addition, results of the WAI percentage indicate that the WAI value varies between 64.6% and 90.7%. This means that all indicators are rated above the mid-point of the Likert scale, which implies that all 30 indicators are considered important and can be used to monitor the project performance.

3.4. Determining key indicators

Reduction of the indicator set to a more manageable number of indicators requires setting a cut-off point. Determining the cut-off point in a Likert scale is very subjective and depends on the aims of the research and how the findings are to be applied. There are several techniques for determining cut-off points: (a) consensus is based on cut-off points at 66.7%, 75%, 80% or 100% agreement [20-27], (b) interquartile range [28, 29], (c) standard deviation [30-32], and (d) group mean value [33].

Among all cited techniques, this study used interquartile range as the effective cut-off point for selecting the indicators to be included in the assessment model. The upper quartile (Q3) is the cut-off point in a distribution above which the highest 25 precent of the WAI scores are located, and the lower quartile (Q1) is the cut-off point below which the lowest 25 percent of the scores are located. (Q2) is usually the median value; it is the value in the data set where there is an equal probability of falling above or below it. Based on the WAI in Table 4, Q1 is 77.3%, Q2 is 80% and Q3 is 85.4%. In this study Q2 or the median has been considered the cut-off point, which delivers a set of 16 indicators achieving 80% and higher on the WAI percentage scale (Table 5).

Table 4. Weighting indicators.

Indicators		Mean	Std. Deviation	WAI%	Rank
Ecological indicators	Climate and microclimatic modifications (e.g. Urban Heat Island effect mitigation; temperature moderation through evapotranspiration and shading; wind speed modification)	4.39	0.76	87.8%	2
	Air quality improvement (e.g. Pollutant removal; Avoided emissions)	4.31	0.75	86.1%	5
	Carbon offset (e.g. direct: carbon sequestration and storage; indirect: avoided greenhouse gas emissions through cooling)	4.27	0.86	85.4%	8
	Reduced building energy use for heating and cooling (through e.g. shading by trees; covering building by green roof and green walls)	4.28	0.79	85.5%	7
	Hydrological regulation (e.g. flow control and flood reduction; regulation of water quality; water purification)	4.31	0.77	86.2%	4
	Improved soil quality and Erosion prevention (e.g. soil fertility; soil stabilization)	3.94	0.89	78.8%	22
	Waste decomposition and nutrient cycling	3.80	0.93	76.0%	25
	Noise level attenuation	3.23	0.96	64.6%	30
	Biodiversity-protection and enhancement (e.g. Communities; species; genetic resources; habitats)	4.22	0.89	84.4%	9
Health indicators	Improving physical well-being (e.g. physical outdoor activity; healthy food; healthy environments)	4.53	0.69	90.7%	1
	Improving social well-being (e.g. social interaction; social integration; community cohesion)	4.21	0.84	84.1%	10
	Improving mental well-being (e.g. reduced depression and anxiety; recovery from stress; attention restoration; positive emotions)	4.33	0.80	86.6%	3
Socio-cultural indicators	Food production (e.g. urban agriculture; kitchen gardens; edible landscape and community gardens)	4.03	0.93	80.7%	14
	Opportunities for recreation, tourism and social interaction (community livability)	4.01	0.81	80.2%	15
	Improving pedestrian ways and their connectivity (e.g. increasing safety; quality of path; connectivity and linkage with other modes)	4.19	0.87	83.8%	11
	Improving accessibility	3.98	0.91	79.6%	17
	Provision of outdoor sites for education and research	3.64	0.96	72.8%	27
	Reduction of crimes and fear of crime (comfort; amenity and safety)	3.63	1.01	72.7%	28
	Attachment to place and sense of belonging (cultural and symbolic value)	3.96	0.93	79.2%	18
	Enhancing attractiveness of cities (e.g. enhancing desirable views; restricting undesirable views)	3.86	0.94	77.3%	23
Economic indicators	Increased property values	3.26	1.14	65.0%	29
	Greater local economic activity (e.g. tourism, recreation, cultural activities)	3.85	0.95	77.0%	24
	Healthcare cost savings	3.95	0.99	79.0%	19
	Economic benefits of provision services (e.g. raw materials; timber; food products; biofuels; medicinal products; fresh water etc.)	3.78	0.99	76.0%	26
	Value of avoided CO2 emissions and carbon sequestration	4.03	0.98	81.0%	13

Value of avoided energy consumption (e.g. reduced demands for cooling and heating)	4.28	0.85	86.0%	6
Value of air pollutant removal/avoidance	4.10	0.88	82.0%	12
Value of avoided grey infrastructure design (construction and management costs)	3.94	0.95	79.0%	20
Value of reduced flood damage	3.96	0.96	79.0%	21
Reducing cost of using private car by increasing walking and cycling (e.g. shifting travel mode)	4.01	0.97	80.0%	16

Additional analysis has been done on the final list of key indicators to identify how the different sectors (Government, academics and practitioners) scored specific indicators (Table 5). It indicates most ecological indicators gained higher levels of agreement from academics; health and sociocultural indicators achieved more attention from practitioners and government sectors, and government sector workers favoured economic indicators.

4. Conclusion

This paper has presented the results from a national and international survey to establish an indicator-based framework to evaluate the level of sustainability of GI projects. This initial framework utilises four categories: ecological, social, health and economics, and consists of 30 indicators derived from existing literature and semi-structured interviews. The Weighted Average Index (WAI) method was applied in subsequent analysis to identify the degree of importance of each indicator. It is a quick technique to identify differences in opinions among respondents, and was utilised to select key indicators out of a set of 30.

Bell and Morse [34] suggest that 20 indicators was manageable for any study, whereas Moles, Foley, Morrissey and O'Regan [35] suggest that up to 40 indicators can be used if time and resources are available. In this study, the selection of indicators was based on a cut-off point of interquartile range (median), which selected all indicators above the median (50th percentile or WAI%≥ 80%). This resulted in selection of 16 indicators, which were rated as either important (score of 4) or very important (score 5). Having achieved more than 80% agreement regarding importance, these 16 indicators were identified as relevant performance indicators for measuring the sustainability level of GI projects. They derive from all four categories; three health indicators, six ecological indicators, three social/cultural and four economic. These results demonstrate that stakeholders pay greater attention to human health and ecological aspects of GI performance (table 5). ‘Improving Physical Well-being’ and ‘Microclimate Modifications’ were identified as the most important indicators and ‘Reducing cost of using private car by increasing walking and cycling’ as the least important.

Table 5. Key indicators set.

Indicators		WAI%	Rank	Leading sector
Ecological indicators (32.43%)	Climate and microclimatic modifications	87.80%	2	G/A
	Air quality improvement	86.10%	5	G
	Carbon offset	85.40%	8	A
	Reduced building energy use for heating and cooling	85.50%	7	A
	Hydrological regulation	86.20%	4	A
	Biodiversity-protection and enhancement	84.40%	9	P
Health indicators (25.91%)	Improving physical well-being	90.70%	1	A/P
	Improving social well-being	84.10%	10	P/G
	Improving mental well-being	86.60%	3	G
Socio-cultural indicators (20.86%)	Food production	80.70%	14	G
	Opportunities for recreation, tourism and social interaction	80.20%	15	G
	Improving pedestrian ways and their connectivity	83.80%	11	P

Economic indicators (20.8%)	Value of avoided CO2 emissions and carbon sequestration	81.00%	13	G
	Value of avoided energy consumption	86.00%	6	G/A
	Value of air pollutant removal/avoidance	82.00%	12	G/A
	Reducing cost of using private car by increasing walking and cycling	80.00%	16	A

G: Government A: Academics P: Practitioners

5. Future Work

This study is part of an ongoing research project designed to develop an indicator-based framework for assessing GI performance. The paper proposed a framework comprising a set of sixteen key indicators based on analysis of experts' perspectives. Understanding the limitations and weaknesses of the proposed framework will require evidence by testing it in case studies. Future research will involve the identification of parameters and sub-indicators for each indicator by applying it to Parramatta CBD in western Sydney (Australia) to calibrate, validate and assess weaknesses and limitations of the proposed framework. The selection of this study area is based on three criteria. First, the Sydney metropolitan strategy 2014 proposed establishment of a Green Grid for Parramatta to supporting sustainable development while increasing the quality of life and livability [36]. Second, this study area represents mixed land-use and high density of commercial and residential with variety of green infrastructure types and potential for additional green spaces and third, the digital spatial data and a complete tree inventory was provided to the researcher by Parramatta city council.

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