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A Decision Support Tool for Green Infrastructure Planning in the Face of Rapid Urbanization

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Abstract: Multifunctional green infrastructure, a key component of compact sustainable cities, is challenged by the pressures associated with rapid urbanization. In this paper, we present a method that uses remote sensing, GIS modeling and stakeholder engagement to produce a decision support tool that communicates the availability and need for green infrastructure benefits. The case study presented is the City of Tshwane, South Africa, a Global South city facing rapid urbanization. We found that this method of mapping green infrastructure benefits can provide simultaneous oversight on multiple objectives for green infrastructure, including climate change adaptation, biodiversity, and equitable distribution of urban green space. We found that low-scoring benefit areas occur in dense urban areas where small-scale nature-based solutions or rehabilitation activities are required. Moderate benefit scores occurred in parts of the city that are vulnerable to urban expansion and densification activities, warranting the careful planning of green infrastructure provision, and that moderate-to-high-scoring areas can be protected as conservation areas. The results are discussed in terms of the role of decision support tools for urban planning practice. Composite indexes can provide important guidance to decision-makers involved in spatial planning and urban upgrading and expansion activities.

Keywords: green infrastructure; decision support tool; multifunctional benefits; remote sensing; sustainability; urban planning; Global South; South Africa; urban greenspace; parks

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1. Introduction

Globally, urbanization is leading to increasingly dense urban environments and/or contributing to urban sprawl in conflict with sustainable development and green cities' objectives [1,2]. In Sub-Saharan Africa, urbanization is compounded by both natural population growth and rural-to-urban migration [3]. While urban sprawl is combatted with planned densification mechanisms such as infill development and consolidation [1], it is seldom implemented with a corresponding expansion of public green space and nature-based solutions to compensate for the loss of private green space during densification activities [4–6]. Similarly, the widespread shortfalls in housing provision in the face of rapid urbanization and a low economic base lead to informal settlement establishment on vacant land and greenfield sites without provision for public green space [3,7]. Thus, both controlled and uncontrolled expansion are driving a critical loss of urban green space and putting pressure on natural ecosystems [1,3,4,6,8].

The provision of and physical access to "green infrastructure" forms part of the suite of solutions deployed to combat many of the challenges facing cities around the world [9,10]. Green infrastructure is defined by the European Commission (2013) as a "strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services" [11], and the multifunctional benefits thereof are well documented as a critical component of climate-resilient, healthy, sustainable compact city planning [9]. It can mitigate climate change risks by alleviating the urban heat-island effect and managing flooding risk [12]. It can strengthen health by improving air quality, encouraging physical activity, and supporting mental health [13–15]. Furthermore, it can conserve urban biodiversity through the preservation and restoration of natural habitats [16,17]. Green infrastructure therefore provides benefits across a range of ecosystem services that collectively contribute to positive socio-economic and environmental outcomes [18,19]. Finally, it offers a number of cultural ecosystem services such as spiritual and religious values, educational opportunities, inspiration, aesthetics, sense of place, and ecotourism [20]

Unfortunately, the provision of and physical access to green space is unequally distributed across socio-economic groupings in many regions. From a justice perspective, this disproportionately affects the poor, such that vulnerable groups have less access to the benefits of urban nature [21,22]; this is a deficit that compounds existing vulnerabilities. Notably, in the Global South there is a reliance on urban nature for provisioning benefits as a poverty-alleviation strategy through urban agriculture, livestock grazing, and foraging of biofuels, food, and medicines [23–28], supplementing household income by up to 33% for those living in informal settlements [29]. In this regard, the planning and inclusion of green infrastructure becomes a critical consideration for the planning of resilient cities, especially in countries with vulnerable populations that require access to green infrastructure benefits.

Advances in technology can be mobilized to support planners in achieving synergies between the multiple benefits of urban green infrastructure by synthesizing information sources. Spatial information on green infrastructure obtained from remote sensing processed with geographic information systems (GIS) provides a technological approach to evidence-based urban planning and can be used to inform needs-based green infrastructure delivery [30,31]. Decision support tools are used to process spatial data into easily understandable maps or for modeling different scenarios for stakeholders and decision-makers [32–35]. Several studies have made progress towards the development of technical approaches that capture the complexity of the multifunctional benefits provided by green infrastructure, providing systematic support for site selection and prioritization of green infrastructure planning [10,30,32,34,35]. Analysis has focused on a range of scales from single green roofs to census tracts between local and regional considerations, while the types of interventions discussed span rewilding, biodiversity conservation, and rehabilitation at the natural end of the continuum to new pocket park establishment, urban greening, and upgrading activities at the urban end of the continuum [10,30,32,34,35]. The distribution of studies has been predominantly in the Global North and has discussed the green infrastructure benefits in isolation of Global South challenges [10], especially in Africa. There are a few exceptions, notably studies in Addis Ababa [36] and Nigeria [37], evidencing that the political will, technical support, and general planning environment challenges are different in most Global South countries. This includes challenges such as institutional inertia, weak spatial management, a lack of integrated city-level decision-making, municipal leadership, and technical capabilities [38]. The omission of studies specifically targeting Global South conditions and challenges represents a considerable gap in research. Despite the gap in Global South-contextualized green infrastructure planning research, remote sensing and computer-aided modeling have been deployed to support the development of municipal Spatial Development Frameworks (SDFs) towards the aims of building climate-resilient cities [39] and achieving the protection of critical biodiversity [40]. These tools have made their way into policy frameworks relating to urban planning and development assessment criteria [39–41], but have made little progress towards integrated and equitable management and prioritization of green infrastructure development for its multifunctional benefits [41,42], representing the second gap our research targets.

This paper focused on green infrastructure in the City of Tshwane, South Africa as a case study context in the Global South. The aim of this study was to develop a GIS-based decision support tool that integrates urban planning objectives for climate resilience and biodiversity into a single multifunctional tool for planning green infrastructure during rapid urbanization, and to do so in co-development with the city representatives that will use it. Building on former studies and the contextual challenges in South Africa, this paper had the following objectives: (1) to present an integrated green infrastructure planning decision support tool for the largest metropolitan area in South Africa, the City of Tshwane (Tshwane); (2) to illustrate how the tool can be used to assess the provision of multifunctional benefits of green infrastructure using GIS to produce composite analysis that can assist city planners in making critical green infrastructure decisions; and (3) to validate the results by comparing them with two existing GIS-based spatial planning tools used by Tshwane planners that assess climate risks and biodiversity separately. The developed methodology has upscaling potential for other cities and countries, and for comparison with tools developed for other countries at local scales. [30,32,35].

2. Materials and Methods

2.1. Study Area

Tshwane metropolitan area (Figure 1) encapsulates the city of Pretoria, which is the administrative headquarters of the Republic of South Africa. It is located in the northern part of Gauteng province, the most densely populated province [43], and the largest single municipality in the country, covering an area of 629,618 ha. Administratively, it is divided into seven regions and 104 districts called "wards". In 2011 it had a population figure of 2,921,488 [44]. South Africa's urban development process is legislated in the Municipal Systems Act (Act 32 of 2000) [45], which sets out the requirements for integrated development plans (IDP) to be updated every five years. These plans are developed in consultation with the public at the ward (local district) level and must be aligned to municipal budgets and realistic time periods. Periodically, the municipal (10 yrs) and regional (5 yrs) spatial development framework (SDF)—a mapped city plan for urban expansion—is developed as part of this process. It is during the development of the SDF that multifunctional green infrastructure assessment can aid in decision-making and planning of the public open space system [46], which is further guided by the Tshwane Open Space Framework and the Bioregional plans for biodiversity protection.

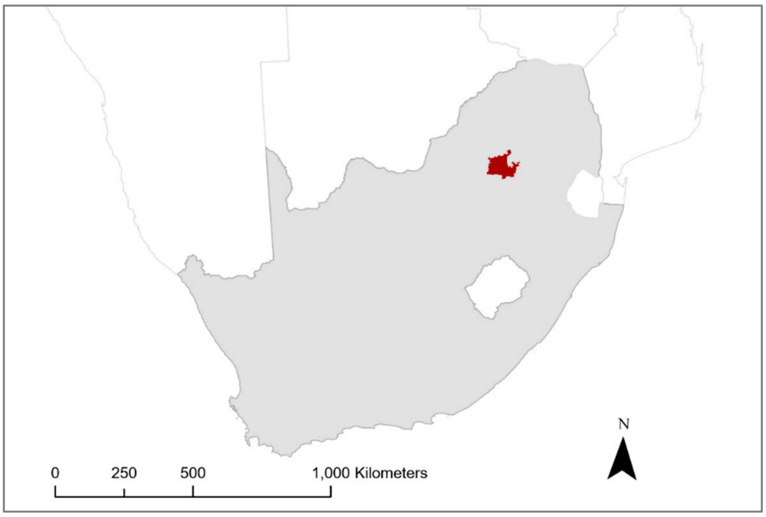

Figure 1. Location of the City of Tshwane metropolitan area in South Africa.

In accordance with the above, Tshwane has a few existing decision-support maps that have been developed for the purpose of providing planning officials with information relevant to negotiating urban expansion and meeting sustainability and climate-resilience goals. There are two such maps, related to biodiversity management and climate adaptation, which have some overlapping relevance to green infrastructure planning [42,47]. The first, the Gauteng C-Plan, is a biodiversity assessment mapping tool which provides information on assessed critical biodiversity areas. The C-Plan is used by local and regional planning departments to determine where nature reserves should be proclaimed, and whether proposed developments fall within Critical Biodiversity Areas (core habitats abbreviated as CBA), or Ecological Support Areas (ESAs) [43]. CBAs are determined by assessing the relative quality and intactness of habitat remnants, the presence of red-listed species, and the extent that the vegetation type remains in its natural state at national scale. It assesses the remnants against conservation targets and determines the extent to which an area needs to be protected according to a classification of either (1.) Important Area, (2.) Irreplaceable Area, or (3.) Acknowledging if it is already a formally Protected Area [43]. The other existing green-infrastructure relevant decision support tool is the City of Tshwane Climate Risk & Vulnerability Assessment (CRVA). It identifies current multiple-climate-risk hazard zones (CRZ), and future multiple-climate-risk hazard (F_CRZ) zones. It incorporates climate change projections, heat-stress, drought, fire risk, flooding risk, urban expansion, and socio-economic vulnerability to identify priority areas for addressing climate resilience challenges [48].

2.2. Decision Support Tool Development

The process followed in this study is outlined in Figure 2. It maps the progress from identification of the locally relevant benefits of green infrastructure, to the assembly of the benefit map [30,32,49]. The steps we followed were: (1.) Identify multifunctional benefits together with stakeholders, (2.) Select maps to represent each benefit, (3.) Engage stakeholders to determine the relative importance of each benefit, (4.) Assembly and quality control, and (5.) Second stakeholder workshop to explore the applications, opportunities, and limitations of the tool. The details of each step are provided in the sub-sections below.

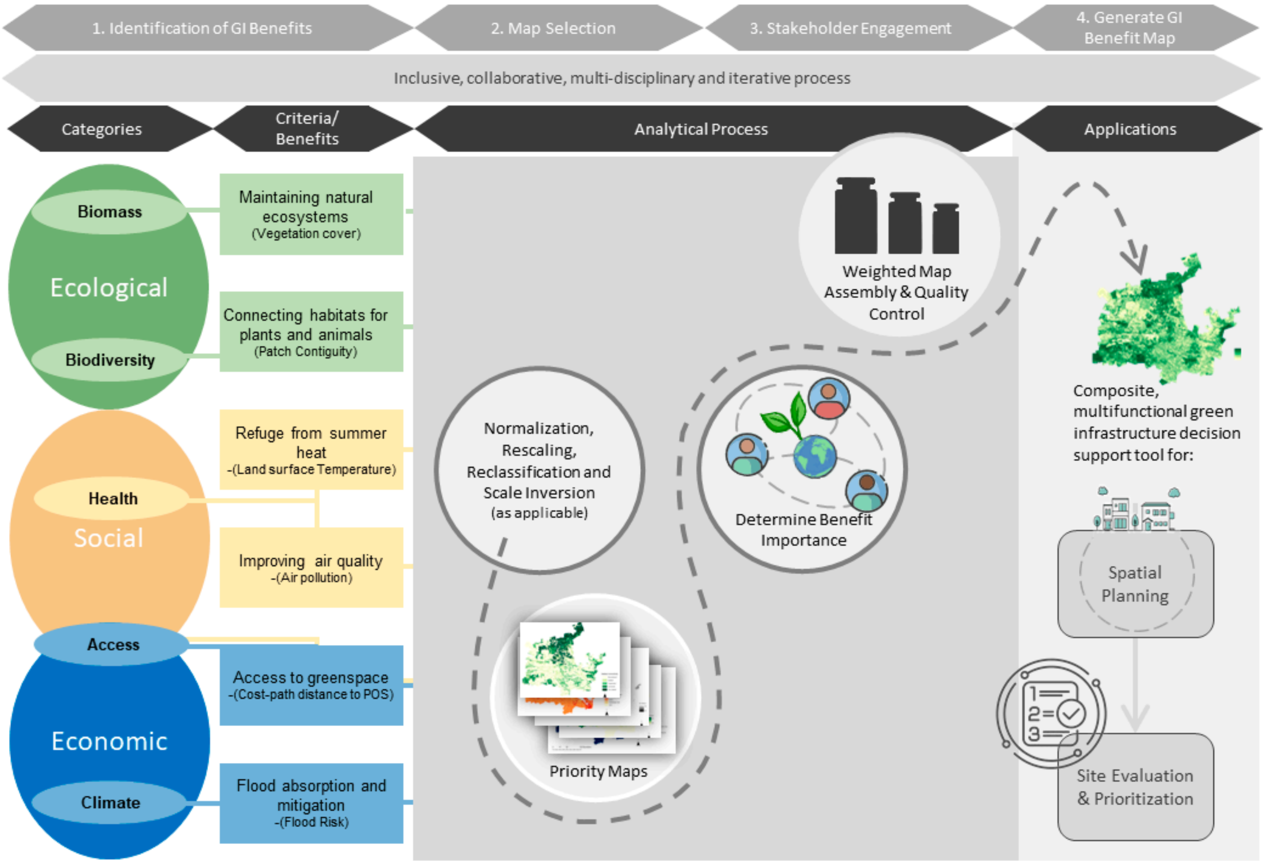

Figure 2. Conceptual figure showing the development process of the green infrastructure benefits decision support tool for the City of Tshwane, South Africa.

2.3. Identification of Relevant Green Infrastructure Benefits

To determine which benefits to include in the study, we searched the literature for approaches previously used to assess access to and distribution of multifunctional green infrastructure benefits [10,30–33,49–53]. Together with key stakeholders from the city, the University of Pretoria affiliated private planning consultants and informed by the literature, we identified three categories, with five sub-categories of benefits, namely natural habitats, biodiversity, health, access, and climate adaptations and resilience (Figure 2). Within those categories, we identified six benefit indicator maps for inclusion. To select the indicator datasets, we consulted national, regional, and local GIS depositories, including the City of Tshwane GIS database, the Council for Scientific Industries Research (CSIR), and the South African Biodiversity Institute (SANBI) for existing expert-generated spatial assessments. Additionally, we considered established spatial analysis methods from remote-sensing data with the aim of finding a suitable and pragmatic indicator set grounded in local context and existing analysis as far as possible.

The selected indicator datasets were as follows: 1. Normalized difference vegetation index (NDVI) to indicate vegetation; 2. Natural patch contiguity to indicate habitat connectivity for biodiversity; 3. Land surface summer temperature to indicate the need for heat stress refugia; 4. Mean cumulative air pollution to indicate the need for pollution mitigation as indicators of the need for health benefits; 5. Cost-path accumulated distance to the open space network as an indicator of the benefits from having physical access to green infrastructure; and 6. Flood risk as an indicator of the need for climate resilience and adaptation benefits. These benefits address cross-cutting issues in multiple categories, for example, climate mitigation benefits have socio-economic and environmental repercussions. The source and development of each of the six benefit indicator maps are described below.

2.4. Health: Heat Stress Mitigation

Under climate risk, we assessed surface temperature to determine where green infrastructure provision can offer a potential mitigation strategy against heat stress and the urban heat island effect (UHI)—the phenomenon of urban warming caused by increased thermal mass in concrete and asphalt surfaces [54]. Remotely-sensed thermal information from the Landsat 8 satellite launched on 11 February 2013 was used to calculate land surface temperature (LST) (https://www.usgs.gov/landsat-missions/landsat-8, accessed on 1 December 2022). Landsat 8 has global coverage at 100 m × 100 m resolution and a revisit cycle of 16 days. LST derived from satellite images is an indirect measure of UHI but can be used in areas without available on-the-ground measuring stations. Half-yearly mean, and max values of temperature and mean across all years from 1 July 2018 to 20 December 2021 were calculated for the City of Tshwane using Google Earth Engine.

2.5. Climate Risk: Flood Absorption

Maps from the City of Tshwane Climate Risk & Vulnerability Assessment (2020 update) were consulted as estimates for the current and potential future impact of climate [48]. The maps are part of an ensemble of high-resolution regional climate model projections of current and future climate change for the City of Tshwane by the end of the 21st century under a low mitigation and high greenhouse gas emission scenario. The underlying climate model is the global circulation model used for the projections of the Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). The original IPCC maps were at 200 km × 200 km resolution, and regional climate models (RCMs) were used to downscale the climate projections to high resolution, detailed projections of future climate change for City of Tshwane at 8 km × 8 km resolution. All details of the downscaling and construction of the climate projections and vulnerability assessment are described in the City of Tshwane Climate Risk & Vulnerability (2020 update) report. The current assessed flood risk hazard was used as an indicator of the risk from flooding in the assembly of the green infrastructure benefit decision support tool.

2.6. Health: Pollution Mitigation

Pollution mitigation was selected as a health benefit. Air pollution presents a great risk to health, and has been linked to cardiovascular, respiratory, and mental health [55]. We used remotely sensed nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon Monoxide (CO) as indicators of air pollution from the Sentinel-5 Precursor satellite. Air pollution data from Sentinel-5 were available globally from 28 June 2018 with daily revisit time. The resolution of Sentinel-5 data is 10 m × 10 m pixels. The cumulative mean for 1 July 2018 to 30 June 2021, and for each year individually, was calculated for City of Tshwane using Google Earth Engine

2.7. Biodiversity: Vegetation Biomass

To assess the extent of vegetation cover, the normalized difference vegetation index (NDVI) was calculated from 10 m × 10 m pixel resolution Sentinel-2 images using Google Earth Engine [56]. The indices were calculated as the median for the time-period 1 January 2018 to 22 December 2021 to obtain the most representative index value across different years and seasons.

2.8. Biodiversity: Habitat Connectivity

To assess habitat for biodiversity provision, we extracted land-cover classes of natural grassland and natural forest, from the South African National Land Cover map, and calculated the patch contiguity in FRAGSTATS [57]. Patch contiguity is a measure of the connectedness vs. isolation of a particular patch of natural habitat. It analyzes each 30 m × 30 m pixel of classified land cover to determine on how many sides (either 4 or 8) the land cover matches the target pixel and within a set radius determined by the user. A maximum score of contiguity is given when 100% of the pixels in all directions within the buffer match the target habitat, and a minimum score is assigned when none of the pixels match. Contiguity is measured on a scale between those extremes. The contiguity buffer was set to 500 m and the pixel analysis was set for 8-side adjacency tests.

2.9. Spatial Accessibility

To measure pedestrian accessibility, we calculated “accumulated cost distance”, which allows for measurement along “least cost paths”. Residential roads and pedestrian routes from the open street map dataset were classified as low-cost routes and major roadways as barriers. This meant that we could calculate distance along pedestrian routes to parks and green networks. We tested the output of several maximum accumulated costs against a straight-line buffer of 2 km in order to produce a layer that most closely represented a maximum 2 km walking distance along the road network. Target green spaces were identified from zoning and spatial frameworks provided by Tshwane and included formally proclaimed nature reserves, district and pocket parks, greenways, riverine corridors, and other legislated open spaces. Distances from green spaces were inverted and reclassified geometrically to categories approximating 300 m walking distance representing “excellent” access for daily use, 600 m walking distance for “good” access or weekly use, 1 km for “fair” access, 1.5 km for “poor” access, and greater than 1.5 km requiring transport for access and indexed 0–9, where 9 was considered “inaccessible”.

2.10. First Stakeholder Engagement Workshop

We hosted a workshop on 15 March 2022 and invited green infrastructure experts from the public and private sector. Suitable participants were identified in collaboration with our project partners in local government. The aim was to deliberate and reach agreement on the relative importance of each selected benefit and to translate that into a weighting of each benefit to be used in the final tool [33]. It was attended by ten public partners from the City of Tshwane. The departments of Environment and Agricultural management (Environmental Planning and Open Space Management, Agriculture and Rural Development, Parks, Recreation and Crematorium, and Nature Conservation), City

Planning, Economic and Spatial Planning, Stormwater management and Housing were also represented. Additionally, three private planning consultants from urban design, landscape architecture, and civil engineering fields were present. The experts were chosen to represent the wide variety of fields that have dealings with green infrastructure planning and management in Tshwane and were identified based on ongoing engagement and related activities undertaken by the research team [33].

The process broadly followed the Delphi method to reach a consensus on the relative importance of each benefit to Tshwane [58]. The workshop had four rounds of valuation. The first round was carried out before the workshop in an anonymous online questionnaire (Annexure A) which was shared in direct emails to workshop attendants. A total of six questions asked respondents to consider how important (on a scale from 1 = not important, to 10 = very important) each of the listed benefits was to Tshwane. The intention of the first round was to prepare participants for the consideration and discussion of the relative importance of each benefit and not for reporting of findings. The second (and remaining) rounds were held in person at the workshop. Participants were first introduced to the maps (Figure 3) and the benefits they represented. After a detailed introduction to each benefit, experts were split into groups of ~ five people, each containing both private and public sector representatives. They were asked to complete a forced-ranking exercise. Each group was given six cards, each presenting a map that illustrated one of the green infrastructure benefits. The workshop participants were asked to rank the benefit maps from most important to least important, reaching consensus within the group through discussion. An observer was present at each group to transcribe notes. In the third round, participants were divided into two new groups and asked to split a total of 100 points between the six benefits. Equal ranking was allowed. Lastly, during the fourth round all participants were asked to deliberate and agree on a final weight for each benefit based on the 100 points given in the previous round.

2.11. *Generating the Multifunctional Benefits Map*

Each of the contributing maps (Figure 3) were first rescaled between 0 and 9 (Figure 3). Four of the maps, namely (B) distance to green infrastructure, (C) mean cumulative air pollution, (D) current flood risk, and (F) land surface temperature, required the scale to be inverted. Thus, greatest distance, greatest air pollution, greatest flood risk, and highest temperature scored zero on the scale of green infrastructure benefits. In the remaining two maps, (A) habitat connectivity and (E) NDVI, the scale was not inverted. The benefit maps were then combined using the weighted sum function in ArcGIS Pro 2.9.1 according to the consensus weights agreed to in the first stakeholder workshop. A final rescaling to arrive at a 0–10 benefit scale was applied to the resulting composite green infrastructure benefit map. Low values represent low levels of benefits and high values represent high levels of benefits.

2.12. *Second Stakeholder Engagement Workshop*

Once the draft tool had been assembled, a second stakeholder engagement workshop was held on 28 October 2022 with 16 city officials. Approximately one third of the attendants were at both workshops. The purpose of the second workshop was to present the DST for continuous co-development and input. The workshop format was based on the “world café” style of engagement [59]. Participants were first introduced to the benefit maps that made up the draft decision support tool. They were then divided into three groups of seven, and each group was given a large piece of paper and pens and asked to draw a mind-map in response to a question. The three questions were:

1. What would make it easier for your organization to use the DST (e.g., packaging guides etc.)?
2. What have we missed? Can you identify the opportunities/synergies and blind-spots/limitations of the tool?
3. How can your department use this tool in their daily activities?

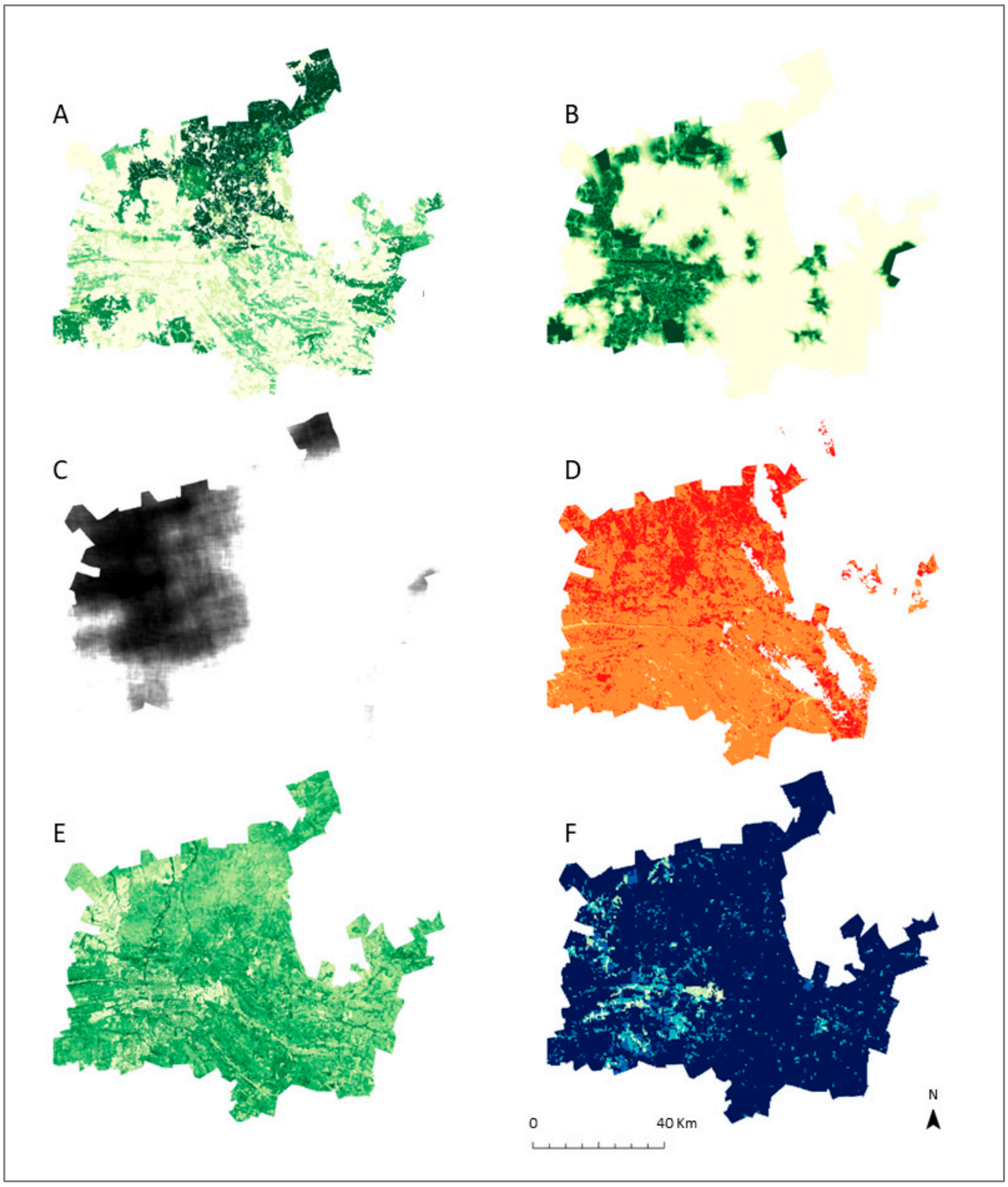

Figure 3. Maps scaled 0–9 representing the multifunctional benefits of green infrastructure. (**A**) Habitat connectivity, (**B**) accessibility measured as the walking distance to public parks, (**C**) mean cumulative air-pollution, (**D**) land surface temperature, (**E**) normalized difference vegetation index, and (**F**) current flooding risk. These maps were assembled into a decision support tool for multi-criteria decision analysis.

Facilitators were placed at each table hosting a group to provide guidance on how to answer the questions and record the conversations. Groups had 20 min to discuss and document their answers and were then asked to move to the next table where they would build on the mind-map of the previous group. After three rounds of 20 min, stakeholders reconvened for a short plenary.

3. Analysis and Quality Control

Analysis was conducted to provide insight into the relationship between existing environmental planning tools used by Tshwane, and the relative distribution of green infrastructure benefits as calculated in our green infrastructure benefit index. Descriptive statistics of the green infrastructure benefit were calculated for each of the categories identified by the C-Plan and the CRVA. The process was repeated for the remaining areas that are not classified by the CRVA and the C-Plan. The data were tabulated in a common database. To determine if there were significant (p-value > 0.05) differences in benefit provision between the groups, an ANOVA was modeled across all land classifications from both tools. To determine if all sub-classes were different from all others, the Tukey Honest Significance Test was performed [60].

4. Results

We observed robust debate and in-depth conversations within the groups and between private consultants and city representatives at the first stakeholder workshop. In the forced ranking exercise, groups noted the interconnectedness of benefits, which made it challenging to consider them individually against the others. One group argued that prioritization of benefits would vary depending on the lens adopted, but that the city is not static concluding that "If we improve access, it will help everything". This group determined their ranking through a social impact lens placing access as the top priority followed by flooding and air-pollution. Another group took a needs-based stance and asked, "What can't we live without?". They considered the benefits from a hierarchical perspective, the backbone of the benefit being provided by vegetation. Without vegetation and biodiversity, there would be no green network to access or provide benefits. The last group decided on a hybrid approach and ranked vegetation and biodiversity first and then air-pollution and flooding. As a result of these discussions, two of the three groups had more similar results in the way in which the benefits were ranked.

When determining the composition of the two new combined groups for the following exercise, we divided the members of the group that adopted the social lens between the other two groups. During this second round, each of the six benefit maps was given a percentage importance out of 100 so that the total value of all maps together made up 100%. Again, the debates were robust, demonstrating the value of the exercise for exchanging perspectives. Both groups agreed that all the benefits should not receive equal weighting. In the first merged group, we noted that the discussions helped to shift perspectives, as expressed by one participant: "Maybe we need to change the way we think about cities, maybe we should focus on people to show them the value of nature.", whilst another expressed the city as a system rather than a series of isolated plots: "There is a need to look at development as [part of] a system, rather than how developers get a plot of land, develop it for density and don't care about how their property fits into the rest of the city." The second merged group began their discussions from the opposite perspectives with members of the group arguing for access to have the smallest versus greatest weighting. They noted the threat that informal settlements present to access and provision as follows: "As long as people lack housing, green spaces continue to be at risk because people want a place to live". The discussion highlighted a need to define the purpose of available land as either obtainable for development or incorporated as green infrastructure into the green network. Much of the unmanaged green space remains undefined and exploitable for urban expansion, as articulated by one participant: "If this is a tool for policy makers, it is necessary to understand the priorities of the City of Tshwane" and "The city needs to know that there is no competition between social and environmental needs".

Consensus was reached in both groups. Although the final values were different, the distribution of the weightings was similar. In both groups, vegetation cover received the greatest weighting, connectivity and access were equally weighted, and air quality and refuge from summer heat received the lowest weighting. The groups justified the weighting of vegetation on the logic that without the vegetation, there is no green infrastructure to provide benefits in the first place. When rejoined into one group consisting of all workshop participants, all agreed that the final score (Table 1) could be reached by averaging the values from the two groups because the distribution was similar.

Table 1. Benefits weighting of importance determined during a stakeholder engagement workshop with representatives from private practitioners and City of Tshwane officials.

GI [1] Category	GI Benefit	Need Addressed	Metric	Weight
Ecological	Vegetation	Maintaining natural ecosystems	Vegetation cover	23.50
Ecological	Biodiversity	Connecting habitats for plants and animals	Patch contiguity	19.25
Social	Health	Equal access for recreation and social well-being	Walking distance	19.25
Economic	Climate	Flood absorption and mitigation	Flooding risk	18.00
Economic	Climate	Refuge from summer heat	Land surface temperature	10.00
Social	Health	Improving air quality	Air pollution	10.00

[1] GI = Green infrastructure.

The values in Table 1 were used to assemble the six benefit maps into a multi-criteria green infrastructure benefit index (Figure 4A). Because the decision support tool targets city planners and developers, means were calculated by municipal budgeting tract (Ward) so that green infrastructure upgrading can be aligned to municipal budgeting priorities in the next spending cycle (Figure 4B).

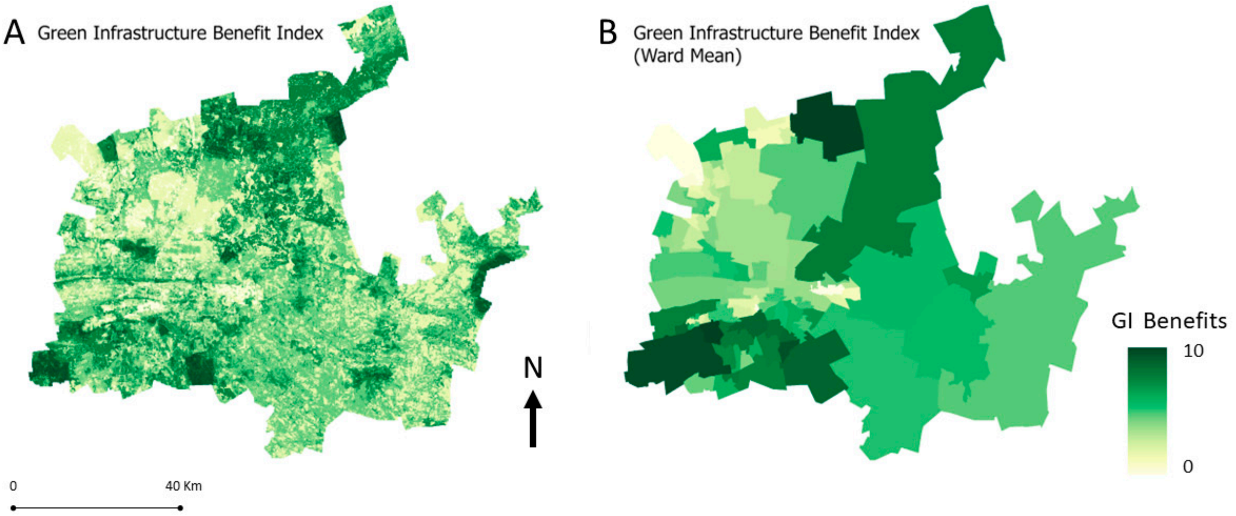

Figure 4. The Green Infrastructure Benefit Index (**A**) shows high levels of green infrastructure benefit provision (dark green) and priority areas for the development of additional green infrastructure projects (light yellow). (**B**) The green infrastructure benefit index is summarized by ward in order to align with municipal budgeting tracts.

The analysis of the distribution of green infrastructure benefits showed that formally protected areas scored highest on the green infrastructure benefit index. The next highest scores were those classified as irreplaceable or as important on the C-Plan. There was no significant difference (p-value > 0.05, Figure 5) between their green infrastructure benefit index scores. Ecological Support Areas, which provide buffers to critical biodiversity areas, and areas projected to be at risk of compound multiple climate hazards in the future scored next. They were statistically near significant, and their means and spread were similar. Current multiple hazard risk zones from the CRVA scored the lowest. The means reported as different by the boxplot were shown to be significant by the Tukey Honest Significance Test (p-value < 0.05).

We found that areas that scored low on the multifunctional benefit scale coincided with the city core and informal settlements. Informal settlements tend to be areas of high-density dwelling, supporting up to 160 dwelling units per hectare [61]. These areas scored low in access to green infrastructure and high in multiple compounded climate risks. Moderately scoring areas tended to coincide with suburban areas, peri-urban areas, and transformed landscapes under agriculture or historical disturbance. When occurring at the urban periphery, these areas are most vulnerable to rezoning and urban expansion. They overlapped with Ecological Support Areas identified by the C-Plan, and Future Multiple Climate Risk Zones identified by the CVRA.

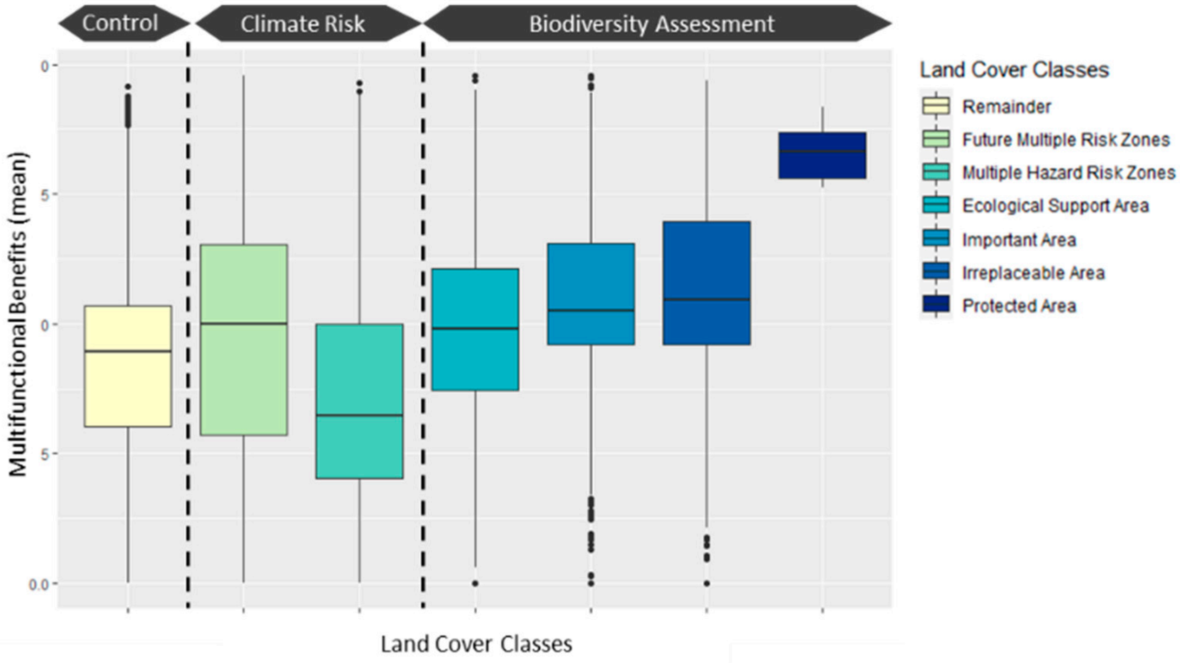

Figure 5. Differences between the means and spread of the measured green infrastructure benefit in the City of Tshwane, summarized by the land cover classes categorized in existing decision tools: Gauteng Biodiversity and Conservation Plan (C-Plan), and Climate Risk and Vulnerability Assessment (CRVA), which prioritize biodiversity protection and climate resilience, respectively.

5. Discussion

This study set out to produce a decision support tool for the planning of green infrastructure in Tshwane. The tool is novel in that it combines cross-cutting multifunctional benefits of ecosystem services into a composite index and is based on a collaborative approach involving public and private stakeholders from conception to validation. This provides integrated indicators of the climate resilience and biodiversity associated with green infrastructure and nature-based solutions to sustainability [5,47]. These overlapping concepts are important to consider in the face of urban expansion, especially when densification mechanisms are enlisted to combat urban sprawl as is being carried out in the South African context [1,61]. This contextual challenge is not unique to South Africa, as densification in the Global South often occurs at the expense of urban green infrastructure [1,42,62]. At the time of the study, the Environmental Planning Department at Tshwane was considering different green open space ratios that could serve as an overarching guideline for development in the city. Although studies in the Global North have been conducted as an overall approach to determining how much green space is enough for human comfort and hydrological processes [63], planning must go beyond mere thresholds and be more responsive to context-specific and projected future needs and risks.

To address the planning challenges, we mapped the provision of multifunctional benefits on a scale from a complete deficit of multifunctional benefits to a maximum provision. We drew on the work of those who have previously built multifunctional green infrastructure maps and frameworks [9,19,32,33,35,64,65] and tested the applicability in a rapidly urbanizing Global South context, using a composite map with a weighted sum on a standardized scale. This is an efficient method simultaneously considering the interactions and compounding effects of overlapping benefit provision or deficit.

The contributing maps can be read individually or together to elucidate the contributors to the benefits provided by the green infrastructure. Proclaimed nature reserves scored the highest because, in addition to having high patch contiguity and vegetative cover (the two layers with the greatest weighting), they also appear on the access layer as a target element due to their official status and management for public access. The correlation between vegetative cover and temperature regulation is well documented as a nature-based solution for combatting urban warming [37,66,67]. Thus, the most built-up areas (city center and informal settlements) were the hottest and were negatively scored by the heat-map against the mean. Similarly, the flood risk assessment considered urban density and socio-economic conditions and reduced the scores in poor areas with high urban density (informal settlements). The most independent layer was the air pollution layer. This was included because green infrastructure can mitigate air pollution providing an indication of the need for pollution management and enhanced green infrastructure [68,69]. Due to the meteorological conditions and dispersed sources of pollution, the distribution of vegetation and air pollution are relatively independent from each other in this dataset.

5.1. Support for Decision-Making

The typical structural elements of decision-making space include *objectives*, *criteria*, *alternatives*, and *trade-offs* [46]. Different theoretical frameworks for decision-making distinguish between descriptive, normative, and prescriptive environments. Descriptive frameworks observe the behavior of decision-makers, prescriptive emphasizes the process of decision-making, and normative environments provide axioms considered rational guidance for making decisions [46].

In considering how the current decision support tool can be used, a combination of prescriptive (process-orientated) and normative (rational) frameworks are adopted [46]. Returning to the elements of decision-making, this tool integrates objectives for achieving green infrastructure planning to provide the multifunctional benefits of climate resilience and adaptation, biodiversity provision, and health and social benefits through physical access. Using the decision environment framework described by Malczewski and Jankowski (2020) [46], the criteria were then translated into benefit (indicator) maps as described by the methods. The workshops precisely showcased the value of our DST as a visual tool for communicating green infrastructure benefits and their distribution. Stakeholders were able to identify its usage potential for negotiations with developers and for aligning objectives for green space across siloed departments. In this way, we see that mapped assessments can provide important communication tools for systemic decision-making and planning of nature-based solutions and green infrastructure [5,47].

The decision support tool should help decision-makers assess the development alternatives for urban expansion that integrate green infrastructure and guide them to choose between conservation actions, climate resilience, and adaptation capacity improvement (noting that these actions are not necessarily mutually exclusive). Additional alternatives include a network of parks and greenways that are strategically positioned within the urban fabric, or the establishment and implementation of nature-based solutions under constrained spatial conditions [4,5,18,46].

The correlation of low-scoring areas with current multiple-climate-risk zones and informal areas with low access to other services demonstrates the urgent need for resource allocation to green infrastructure upgrading. This lack of attention to green space in informal developments has been reported in other studies in Africa [70,71]. We agree with Cobbinah et al. (2015) [71] that developments should therefore aim to improve access to safe, quality urban green space, and ensure that overlapping benefits are provided and include climate change mitigation. The types of developments required in low-scoring areas will need to be interrogated for feasibility at site-specific scales, and may include street trees, river system cleanup and restoration, park upgrading, land clearing for park installation, urban greening, rain gardens, and other examples of sustainable urban drainage systems [9,18,72]. New developments at the urban periphery in areas that currently provide intermediate levels of green infrastructure benefits need to be carefully planned to retain green networks and ecological corridors [73]. The DST, therefore, presents an opportunity and necessary alertness to the risks of green infrastructure benefit loss when rezoning activities are considered. Similarly, protected conservation areas provided the greatest level of multifunctional benefits, but only slightly more than unprotected areas. The formal protection meant that they were included as target areas in the accessibility layer for public access, but the development of this layer did not take population density or (projected or informal) growth into consideration, so while they often do provide a publicly accessible amenity, they might occur in remote areas.

5.2. Trade-Offs between Green Infrastructure Planning Decisions

In any decision environment decision-makers need to be aware of the trade-offs that come with making a particular spatial choice, especially those that result in large scale land-cover change [74]. Sussams, Sheate and Eales (2015) [72] identified the trade-offs and synergies for green infrastructure land use and development. For example, habitat protection and tourism are synergistic while they identify conflict between provisioning ecosystem services such as agricultural production and recreational activities. Yet, there are examples of spatial arrangements that combine urban agricultural activities and play spaces in a mixed-use format, such as the juxtaposition of parks and urban farmland or allotment gardens. Perhaps more relevant are the noted conflicts between urban agriculture and flood reduction in a constrained urban landscape [75]

In the rapidly urbanizing context of the Global South, the most critical decision faced by planners is whether to earmark a particular piece of land for densification, or full or partial retention as green infrastructure, and how to decide which pieces of green infrastructure should be retained and/or upgraded as public parks during development. Once densification has taken place, the feasibility of reinstating green infrastructure becomes increasingly challenging and is increasingly limited to small-scale interventions [9,18,76]. Therefore, the scope of alternatives is constrained along the continuum of available green infrastructure space. Figure 6 presents a decision tree that exemplifies the process path that can be navigated towards selecting from the development alternatives as applied to the spatial planning of green infrastructure in line with the abovementioned findings. The decision tree is purely illustrative, suggesting a guiding template that decision-makers and practitioners should themselves co-develop based on their own principles, priorities, and interventions, taking local feasibility and resources into account.

5.3. Limitations of Scope and the Need for Supplementary Methods

The green infrastructure benefit index's limitations can be used to identify directions for future research. Firstly, while it provides an empirical example of how decision support can guide choices about green infrastructure developments, it does so without assessing the quality and user experience of the existing green infrastructure on the ground. Specifically, several studies have indicated the neglect of user preferences of green spaces in sub-Saharan Africa, indicating that on-the-ground observations are an important contribution to the experience of a park [71,77]. Quality measures are usually measured within a green space based on the measurement of user preferences or the presence of features that are considered to be indicators of good-quality park space (e.g., tree canopy, water, walkways, benches, and diverse vegetation). User preferences can be assessed through ethnographic field studies, and social surveys [78–80]. The measurement of quality through the presence of specific park features is measured through field observations or machine learning algorithms [78,81]. Assessments of multifunctional benefits and park quality on the ground can therefore be obtained by carrying out site surveys or through community engagement on preferences. Secondly, several of the contributing layers could be improved through future developments in satellite sensing technology and computing advancements. The FRAGSTATS analysis of patch contiguity processes pixels of a minimum of $0.015'$, which reduced the output resolution of the contiguity map; more fine-scaled information and modeling capacity increases the ability to map unique features at the site level. Thirdly, the development of complex modeling capabilities will provide additional insights in the future [36,82]. Fourth, certain physical features are difficult to map without a site survey. For example, we could not reliably detect the position of gates, fences, and entry points from satellite data. Fifth, being a spatial tool at municipal scale, our analysis is limited to spatial access and does not consider the wider socio-political mechanisms of access, such as knowledge and social relations, shaping the ability of someone to derive benefits [83]. Although it would be near impossible to assess at city scale, research on social modes of access is important for understanding the community structures and amenity features that foster sense of safety and appropriate usage levels [84–86]. Sixth, while habitat structure can be derived from hyper-spectral classification, such as NDVI, assessing species diversity and dispersal requires either citizen science inputs or local site surveys of species presence [87–89].

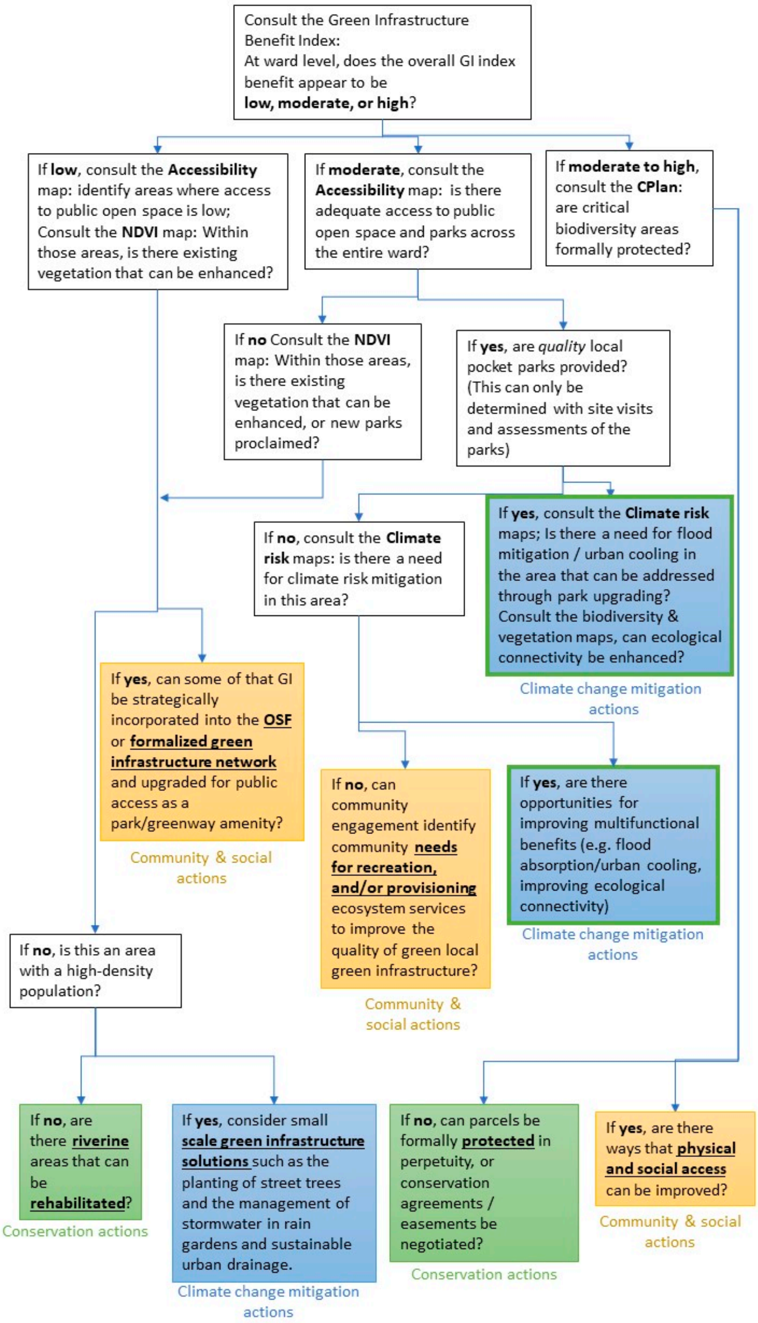

Figure 6. An example of a decision tree for guidance on selecting from the alternative development activities which can be implemented in response to the information in the green infrastructure benefit index map.

In summary, a map derived from remotely sensed data provides information at regional and neighborhood scales for oversight of the green infrastructure network but lacks detail of the social preferences and modes of access and local site conditions, including ecological integrity and other quality features.

6. Conclusions

In this paper we presented a decision support tool that is based on a green infrastructure benefit index and discussed its potential to support the decision-making process in the rapidly urbanizing context of the Global South. We argue that a multifunctional benefit perspective can pull together planning objectives for compact sustainable cities, supplementing biodiversity conservation and climate resilience and can provide decision support for examining the spatial planning alternatives for urban expansion and densification that incorporates green infrastructure. The tool provides a landscape scale, top–down approach that works best when integrated with local site surveys and social engagement to ensure both environmental quality and equitable outcomes. Its limitations lie in its inability to reflect the particularities of local site conditions and social preferences. Despite these limitations, the tool could be a valuable first step in decision-making processes in cities where the capacity of public sector officials is often tested and strained. The approach importantly considers local stakeholder priorities in the development of decision support systems and reflects the importance of considering these perspectives in sustainable development alternatives that are place-appropriate. We believe the co-learning practices presented in this paper will also help create a much-needed deeper understanding of competing development priorities and the ways in which the different development lenses adopted can alter the prioritization of different outcomes. The findings make an innovative contribution by bringing technological solutions together with participatory techniques for the development of decision-support tools. This is significant because involvement of users will improve the likelihood that research outputs are immediately adopted and integrated into policy. The technology is globally available and the methods are readily replicable and adaptable, making them suitable for testing and scaling in other contexts. We would like to see future research and development activities that take a collaborative and action-oriented approach to green infrastructure development and involves greater interrogation of the social modes of access and their implications for planning decisions in Global South contexts.

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Informed Consent Statement: All participants were informed about the purpose of the study and possible means of dissemination of the results. Participation was voluntary, with consent and all participants remained anonymous.

Data Availability Statement: Data can be requested from Peta Brom brompeta@gmail.com.

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