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A green infrastructure spatial planning model for evaluating ecosystem service tradeoffs and synergies across three coastal megacities

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A Green Infrastructure Spatial Planning model for evaluating ecosystem service tradeoffs and synergies across three coastal megacities

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Abstract: A growing number of cities are investing in green infrastructure to foster urban resilience and sustainability. While these nature-based solutions are often promoted on the basis of their multifunctionality, in practice, most studies and plans focus on a single benefit, such as stormwater management. This represents a missed opportunity to strategically site green infrastructure to leverage social and ecological co-benefits. To address this gap, this paper builds on existing modeling approaches for green infrastructure planning to create a more generalizable tool for comparing spatial tradeoffs and synergistic 'hotspots' for multiple desired benefits. I apply the model to three diverse coastal megacities: New York City, Los Angeles (United States), and Manila (Philippines), enabling cross-city comparisons for the first time. Spatial multi-criteria evaluation is used to examine how strategic areas for green infrastructure development across the cities change depending on which benefit is prioritized. GIS layers corresponding to six planning priorities (managing stormwater, reducing social vulnerability, increasing access to green space, improving air quality, reducing the urban heat island effect, and increasing landscape connectivity) are mapped and spatial tradeoffs assessed. Criteria are also weighted to reflect local stakeholders' desired outcomes as determined through surveys and stakeholder meetings and combined to identify high priority areas for green infrastructure development. To extend the model's utility as a decision-support tool, an interactive web-based application is developed that allows any user to change the criteria weights and visualize the resulting hotspots in real time. The model empirically illustrates the complexities of planning green infrastructure in different urban contexts, while also demonstrating a flexible approach for more participatory, strategic, and multifunctional planning of green infrastructure in cities around the world.

Keywords: green infrastructure, urban resilience, spatial planning, ecosystem services, urban sustainability, megacities

1. Introduction

Coastal megacities concentrate risks and opportunities for resilience. On the one hand, densely populated urban areas are highly vulnerable to disasters and climate change impacts while also being responsible for a large share of global consumption, energy use, and carbon emissions (Duren and Miller 2012, Klein *et al* 2003). Urbanization in coastal areas also negatively impacts the local environment, for example through subsidence, pollution, habitat fragmentation, and loss of ecosystem services (Blackburn and Pelling 2014). On the other hand, large cities may be part of the solution, presenting certain efficiencies and economies of scale (Seto *et al* 2010).

There are numerous proposed strategies for mitigating the negative impacts of urbanization and enhancing urban resilience, such as high-albedo 'cool roofs' and pavements, strategic building and street designs, and public transportation (Coutts *et al* 2010). While previous studies have examined the relative merits of various strategies (c.f. Georgescu *et al* 2014), it is worth looking more closely at green infrastructure because it is increasingly promoted in both research and practice (Finewood *et al* 2019, Mcphearson *et al* 2015). Definitions of green infrastructure vary, but it generally refers to vegetated areas such as parks, greenways, rain gardens, or green roofs (Koc *et al* 2017). A growing number of researchers, government agencies, and organizations are working to expand green infrastructure in cities worldwide – and megacities are often leaders in environmental policies with significant economic resources for implementation (Parrish and Zhu 2009) – yet "how applicable and effective these approaches can be in megacity contexts and how they can be implemented is an important arena for experimentation and information sharing" (Li *et al* 2015, p 609).

Green infrastructure is particularly appealing and widely advocated because it is thought to provide a multitude of desired social, ecological, and technical benefits, often termed ecosystem services (Tzoulas *et al* 2007, Hansen *et al* 2017). Commonly cited benefits include improved stormwater management (Eckart *et al* 2017), improved water and air quality (Pugh *et al* 2012, Wagner and Breil 2013, Davis *et al* 2009), mitigation of the urban heat island (Norton *et al* 2015), improved physical and mental health (Amano *et al* 2018), habitat improvements (Benedict and McMahon 2002), and increased property values (Netusil *et al* 2014). Green infrastructure's ability to provide multiple co-benefits may be especially important for coastal megacities, where there are many competing demands for limited land (Von Glasow *et al* 2013).

Despite numerous claims about the multifunctionality of green infrastructure, most empirical studies and plans focus on one or a few of these benefits – especially stormwater and flooding management (Venkataramanan *et al* 2019). Research on potential synergies and tradeoffs between ecosystem services or green infrastructure functions is also limited (Lovell and Taylor 2013, Kremer *et al* 2016). In general, green infrastructure impacts are localized, therefore it matters how green infrastructure is distributed across the city (Hansen and Pauleit 2014, Heckert and Rosan 2018). Yet efforts to strategically integrate different social and ecological benefits into city-wide green infrastructure planning have so far been limited, and there is a clear need for "scientists to deliver more practically-oriented tools and concepts" for doing so (Hansen *et al* 2019, p 108).

A few such tools have been developed for individual cities, which typically combine multiple GIS criterion layers to identify priority areas for green infrastructure (Madureira and Andresen 2013, Heckert and Rosan 2016, Kremer *et al* 2016, Sharma *et al* 2018). This paper builds on one of these models, the Green Infrastructure Spatial Planning (GISP) model developed by Meerow and Newell (2017) and initially applied to Detroit, Michigan. Here I not only increase the generalizability of the approach by applying it to three coastal megacities – New York City (NYC), Los Angeles (LA), and Metropolitan Manila (Manila) – but also improve its utility as a decision-support tool by developing an interactive web-based application. Applying the model to three cities enables cross-city comparisons and reveals broader ecosystem service synergy and tradeoff patterns.

These three cities were selected based on several criteria. First, they are classified as coastal megacities, at the center of urban agglomerations with over ten million residents and located within a 50 meter elevation and 100 kilometer distance of mean high water (Blackburn and Pelling 2014). In fact, NYC and LA are the only two U.S. cities classified as such. Second, the cities are all vulnerable to multiple natural hazards (UN DESA 2011, Sundermann *et al* 2013). Third, the cities vary in terms of the scope of their green infrastructure planning. NYC is several years into the implementation of a comprehensive, multi-million dollar green infrastructure master plan (Kremer *et al* 2016). LA has several ambitious plans and programs, but all in the early stages. Metro Manila only has localized initiatives. An important motivation for including Manila in the study is to test the model's utility outside of the U.S., in a relatively data scarce environment. From a practical perspective, the American cities were selected because of accessibility, and the final selection of all three cities was made on the basis of practical considerations associated with the stakeholder survey.

Next, I outline the methodology used to develop the GISP model for the three cities, including the mapping of individual model criteria, evaluation of synergy and tradeoff patterns, stakeholder weighting, and the web-based tool. I present the results in section 3. In the fourth and final section, I discuss the implications of these findings, important model limitations, and possible future extensions.

2. Methodology

The GISP model provides a general approach for mapping priority areas where green infrastructure can be strategically placed to maximize ecosystem service benefits and assess spatial tradeoffs (Meerow and Newell 2017). The model combines GIS-based multi-criteria evaluation and stakeholder-derived weights. The six criteria, which represent commonly cited benefits of green infrastructure include: 1) managing stormwater; 2) reducing social vulnerability; 3) increasing access to green space; 4) reducing the urban heat island; 5) improving air quality; and 6) increasing landscape or habitat connectivity. These are combined and weighted based on local expert stakeholders' planning priorities. This paper improves the initial model by updating the data sources, comparing findings across three very different cities, and developing a new web-based interactive tool.

2.1 Mapping criteria

Wherever possible, similar datasets were used for the three cities, but especially for Manila, this was not always possible. This limitation is further discussed in section 4. For each of the six criteria, indicators are aggregated at the smallest spatial unit for which data was readily available. For NYC and LA that is the 2010 census tract, and for Manila the barangay or village (the smallest local government and census unit). Official census boundaries were clipped to include only land areas. Since some indicators consider population, tracts with no population (e.g. parks, water features) were excluded from analysis. The model is constructed from widely available spatial datasets selected in consultation with local experts. Data for each criterion was processed and mapped separately; with a linear scale transformation ("maximum score" – see appendix A for equation) applied to measurement scales so that all criterion scores were standardized to range from zero to one (Malczewski 1999). The selection rationale for each indicator, the data sources and processing steps are outlined below and summarized in Table 1.

2.1.1 Managing stormwater

To identify priority areas for green infrastructure based on stormwater management, estimates of percent impervious surface were calculated for each spatial unit. Impervious surfaces such as buildings, roads, and pavement prevent water from infiltrating into the ground, and are therefore more likely to produce runoff that collects pollutants, strains sewer infrastructure, and potentially causes flooding (Shuster et al 2005). Percent Impervious (PI) data sets were acquired for each city from NASA's Socioeconomic Data and Applications Center (SEDAC). The Global Man-made Impervious Surface (GMIS) Dataset is a product prepared from 2010 Landsat data with a spatial resolution of 30 meters (Brown de Colstoun *et al* 2017).

Table 1. GISP model criteria and data sources for the three megacities

Resilience planning priority	**Criterion**	**Spatial attributes (Indicator)**	**Los Angeles data source**	**New York City data source**	**Manila data source**
Managing stormwater	Stormwater hazard	Percent impervious surface	Global Man-made Impervious Surface Dataset (2010) from NASA SEDAC's Global High Resolution Urban Data from Landsat Collection	Global Man-made Impervious Surface Dataset (2010) from NASA SEDAC's Global High Resolution Urban Data from Landsat Collection	Global Man-made Impervious Surface Dataset (2010) from NASA SEDAC's Global High Resolution Urban Data from Landsat Collection
Reducing social vulnerability	Social Vulnerability Index (SoVI)	Combination of indicators associated with social vulnerability to natural hazards	SoVI data for 2010 created by the Hazards and Vulnerability Research Institute (2015)	SoVI data for 2010 created by the Hazards and Vulnerability Research Institute (2015)	SoVI data for 2010 calculated for cities in Metro Manila by See and Porio (2015)
Increasing access to green space	Lack of access to parks	Park access indicator	Population weighted distance to nearest park from buildings within tract based on Open Street Map (Logan et al., 2019)	Population weighted distance to nearest park from buildings within tract based on Open Street Map (Logan et al., 2019)	Average distance to nearest park within barangay based on Open Street Map (Logan et al., 2019)
Reducing the urban heat island effect	Land surface temperature	Average land surface temperature for three months	LST estimated using Landsat 8 thermal infrared, near infrared, and red bands.	LST estimated using Landsat 8 thermal infrared, near infrared, and red bands.	LST estimated using Landsat 8 thermal infrared, near infrared, and red bands.
Improving air quality	Severity of air pollution	Estimated severity of air pollution	Total cancer risk from National Air Toxics Assessment (EPA 2014)	Total cancer risk from National Air Toxics Assessment (EPA 2014)	Percent of total area within 200 m of a major road. (University of Philippines School of Urban and Regional Planning, 2013)
Increasing landscape connectivity	Physical connectedness of wildlife habitat (vegetated	Patch cohesion Index (Fragstats)	Physical connectedness of tree canopy (LA Regional Imagery Acquisition Consortium (LAR-IAC), 2011)	Physical connectedness vegetated areas (excluding built-up and water areas) based on ECM (O'Neil-Dunne et al., 2014).	Physical connectedness of wildlife habitat (excluding built-up and water areas) using land cover data from NAMRIA (2010)

2.1.2 Reducing social vulnerability

Green infrastructure has been linked to numerous social and community benefits, thus it may be strategic to site new developments in disadvantaged, or more socially vulnerable, communities. There are many possible indicators for social vulnerability, arguably the most well-established being the Social Vulnerability Index (SoVI) (Cutter *et al* 2003, Cutter and Finch 2008). For LA and NYC, the SoVIs were calculated specifically for the cities by researchers at the Hazards and Vulnerability Research Institute using 27 variables from the 2010 Decennial Census and Five-Year American Community Survey, 2006-2010 for all census tracts. For NYC the index had 7 factors accounting for 70% of the variance, and LA's had six accounting for 68%. No SoVI has been calculated at the barangay level for Manila, but See and Porio (2015) have created a SoVI based on 2010 census data for each of the 16 cities and one municipality that make up Metropolitan Manila. Without any addition data for the barangays, I had to simply assign each barangay the SoVI value of the city it is in, although this likely obscures intracity variation given the Philippine's high income inequality (UN-Habitat 2013).

2.1.3 Increasing access to green space

Many studies have shown that green spaces are not evenly distributed across cities, which is problematic given their many benefits (Wolch *et al* 2005, Nesbitt *et al* 2019). New investments in green infrastructure could be sited in communities with less access to green space to address this inequity. To identify these areas in New York and Los Angeles, I used an indicator representing the population weighted mean distance to the nearest park for all buildings within a census tract (Logan *et al* 2019). Logan et al.'s model uses open source data from OpenStreetMap (OSM) and the Open Source Routing Machine (OSRM; http://project-osrm.org/) to calculate the walking distance between every building (using the city's building footprint data) and the nearest park (OSM). The total census block population (from US Census 2016 TIGER/Line Shapefiles) is divided evenly among the buildings in that block. This indicator is calculated by multiplying every building's assigned 'population' and park distance, summing these values for the tract, and dividing this by the total tract population. In Manila this approach was modified because no building footprint or population dataset could be identified. A 100-meter grid of 'origin' points was overlaid across Manila, the distance from each origin to the closest park boundary point calculated, and the average distance determined for all origin points within each barangay. This indicator is significantly different from that used in NYC and LA, since it is not weighted by population.

2.1.4 Reducing the urban heat island effect

Vegetation can cool the local environment, thereby helping to mitigate the urban heat island effect (UHI) (O'Neill et al 2009). As an indicator of the UHI in each city, I used Land Surface Temperature (LST) datasets calculated from Landsat 8 Thermal Infrared Sensor (TIRS) using the Radiative Transfer Equation-Based Method (Yu et al 2014). Landsat scenes were identified based on three criteria: 1) less than 10% land cloud cover, 2) as close to the summer months of the region as possible, 3) the most recent scene available for the study area. June 12, 2017 was used for NYC, July 11, 2017 for LA, and February 13, 2016 for Manila. Manila had few scenes without cloud coverage. While LST is widely used as an indicator of UHI because of its availability, surface temperatures may not reflect the temperatures people experience as well as air temperatures, although the two are generally correlated (Good 2016).

2.1.5 Improving air quality

Vegetation can reduce air pollution, such as particulate matter and ozone (Pugh *et al* 2012). To identify high priority areas for air quality improvement in NYC and LA, I used the U.S. EPA's 2011 National Air Toxics Assessment (NATA). The EPA produces this "screening-level" model of respiratory risks to human health from outdoor air toxics at a census-tract scale, which are designed for identifying "geographic patterns and ranges of risk" (U.S. Environmental Protection Agency 2015). While this data has many limitations, it is freely available for the entire United States (Chakraborty *et al* 2017). I used the total cancer risk estimates for each tract. Unfortunately, no barangay-level air quality model could be identified for Manila. Transportation-related emissions are among the most harmful to public health, and concentrations of air pollutants are higher closer to major roadways (Design for Health 2007). Therefore, I used proximity to major roads as a proxy for air pollution hotspots. I calculated a buffer of 200 meters (the threshold used by the U.S. Department of Transportation for "proximity to major roadways") around all roads with more than four lanes, and then calculated the percentage of each barangay's total area within the buffer.

2.1.6 Increasing landscape connectivity

Vegetation and green spaces provide refuge and resources for many species, but this remaining habitat becomes fragmented in urban areas, resulting in fewer ecosystem services (Mitchell *et al* 2013). A possible solution is to connect and expand remaining green spaces, and research suggests such networks can provide valuable habitat (Kong *et al* 2010, Zhang *et al* 2019). Fragstats is a free and easy-to-use software program for landscape connectivity calculations (McGarigal *et al* 2012). Within Fragstats, the Patch Cohesion Index provides a measure of the physical connectedness of 'habitat patches' across a landscape. I calculated the

Patch Cohesion Index for vegetated land cover for each spatial unit in each city, assuming that these areas would provide habitat to various species. This does make the results subject to edge effects, since each tract is analyzed in isolation. In NYC, I used the high-resolution Ecological Covertype map (O'Neil-Dunne *et al* 2014) and combined areas classified as "forested wetland," "freshwater wetlands," "maintained lawn and shrubs," "maritime forest," "other tree canopy," "tidal wetlands," "upland forest," and "upland grass and shrubs" into the habitat patches. In LA I used tree canopy areas as the habitat patches (LAR-IAC 2011), and because so much of Manila's land cover dataset (NAMRIA, 2010) was classified as "built up" I included all areas categorized as "mangrove forest," "open forest," "broadleaved," "cultivated annual and perennial crops," "barren land, grassland, marshland" and "wooded land (shrubs, wooded grassland)" as habitat patches.

2.2 Determining stakeholder priorities and criteria weights

In addition to mapping the six criteria, I conducted fieldwork in each of the three cities and co-organized stakeholder meetings (LA in February 2016, Manila in August 2016, and NYC in January 2017) that brought together local experts and decision-makers for green infrastructure planning. At all three events, I introduced the model and I asked participants to complete a survey comparing the relative importance of the six model criteria using three different methods: rating, ranking, and pair-wise comparisons (For details see Appendices B & C). While not representative, the survey is meant to gather a range of expert opinions in each city to give some indication of the relative importance of the criteria. The results from the pair-wise comparison survey questions were aggregated to produce weights. Pair-wise comparison analysis was done using Excel-based AHP calculator (Goepel 2013) or AHP Survey package (Cho 2019). I then used weighted linear combination to develop combined 'hotspot' maps for green infrastructure expansion.

2.3 Web-based interactive tool

Recognizing that the survey results may not be representative and that priorities may change over time, I also created a web-based tool that allows users to adjust the weights and immediately visualize the combined and weighted results (www.gispmodel.com; Meerow 2019). The tool was developed using R Shiny Applications (Chang *et al* 2019) and a similar structure a tool for conservation planning (Coristine *et al* 2018).

3. Results

Developing the GISP model for three diverse megacities highlights the complexities of planning green infrastructure to maximize multiple resilience benefits. Priority areas for green infrastructure clearly differ depending on decision criteria. Some spatial tradeoff and synergy patterns are consistent across the three cities, while others differ. Local priorities also seem to vary between the three cities, confirming the need for stakeholder consultation and customized weighting schemes.

The six preliminary individual criterion maps for each of the cities are shown in Figures 1-3. In each case, the darker shaded spatial units represent areas that are higher priority for green infrastructure development based on the model. It is clear that spatial priorities vary across the criteria. I examine these tradeoff and synergy relationships quantitatively by running Pearson's bivariate correlations between the criteria in each city (Figure 4)

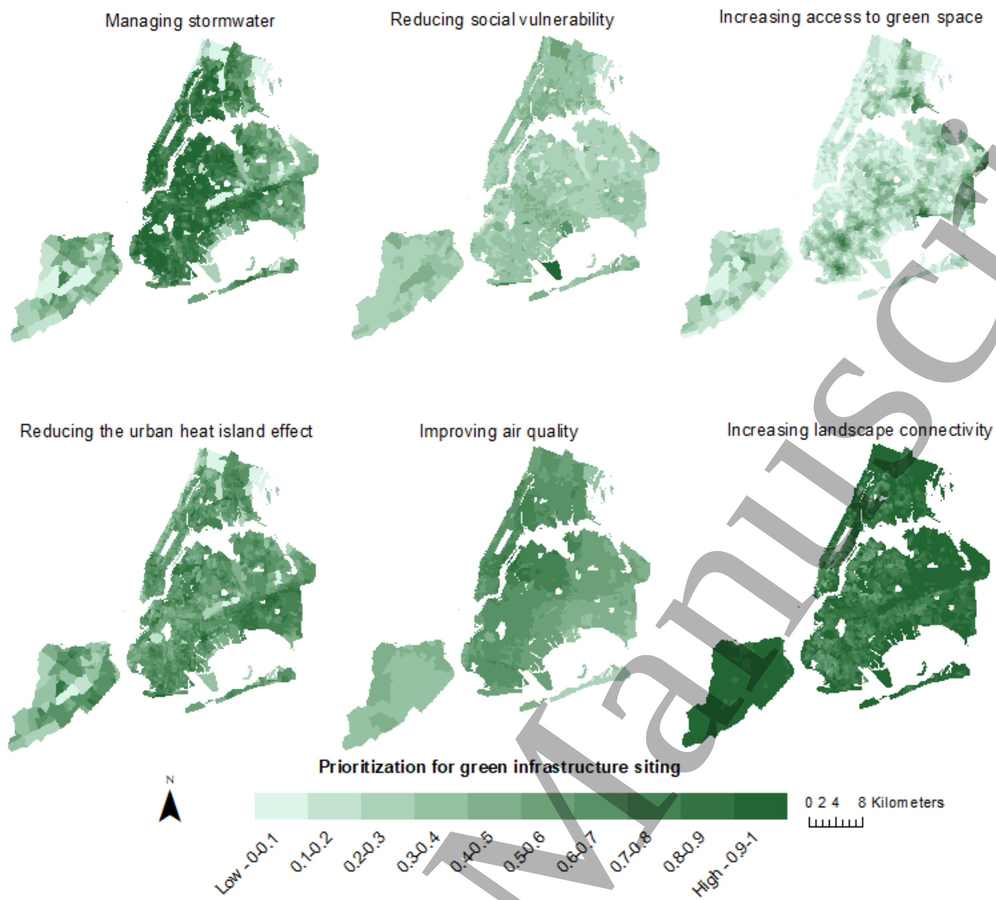

Figure 1 New York Green Infrastructure Spatial Planning (GISP) model criteria
*Note***:** Each map shows the relative prioritization of census tracts in New York for green infrastructure based on commonly cited benefits of green infrastructure.

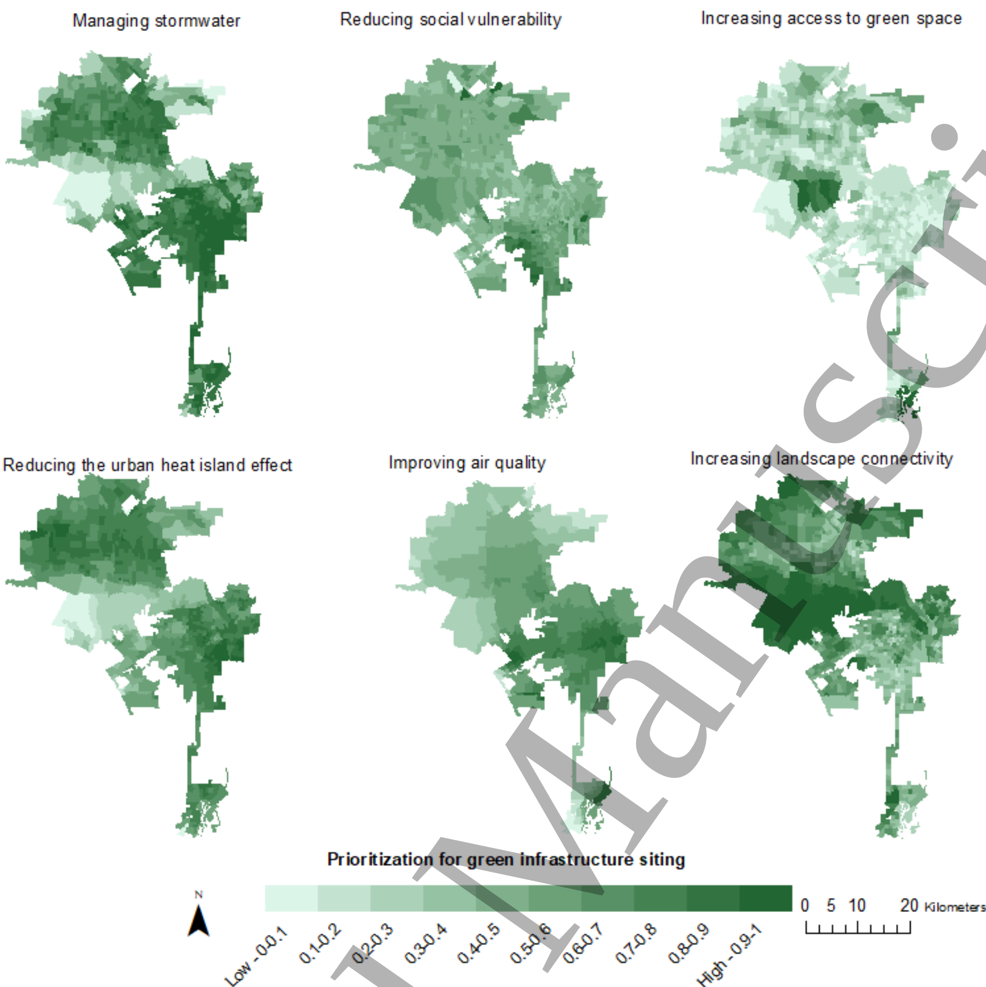

Figure 2 Los Angeles Green Infrastructure Spatial Planning (GISP) model criteria
*Note***:** Each map shows the relative prioritization of census tracts in Los Angeles for green infrastructure based on commonly cited benefits of green infrastructure.

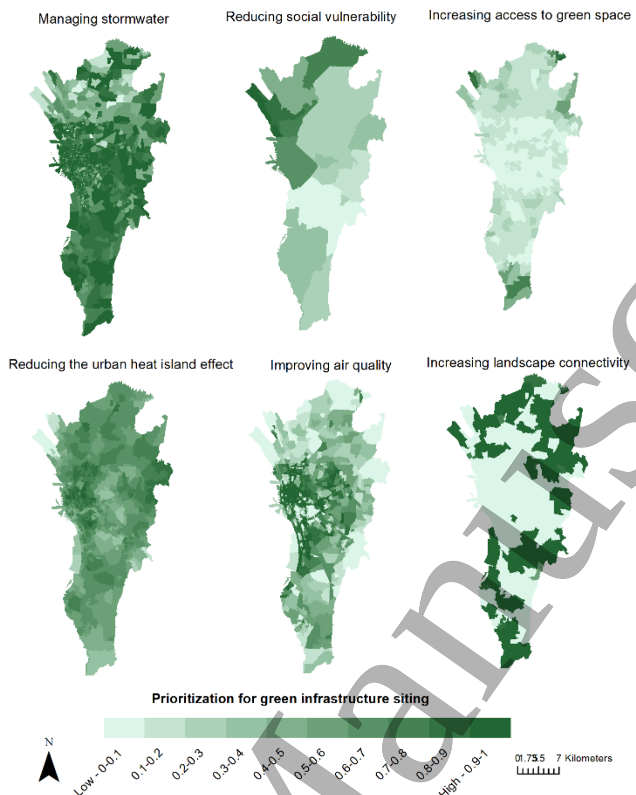

Figure 3 Manila Green Infrastructure Spatial Planning (GISP) model criteria
Note: Each map shows the relative prioritization of barangays in Manila for green infrastructure based on commonly cited benefits of green infrastructure.

Figure 4 Spatial tradeoffs and synergies between GISP model criteria
Note: The larger the diameter and shading of circles depict the Pearson's correlation coefficient for GISP model criteria. A larger circle indicates a stronger negative (red) or positive (blue) relationship. Circles marked with an "X" are not statistically significant.

3.1 Analyzing spatial synergies and tradeoffs

Correlations between criterion scores (Figure 4) reveal potential spatial tradeoffs and synergies between planning priorities. A positive correlation indicates a spatial synergy, whereas a negative relationship indicates a tradeoff. Certain correlation patterns are consistent across the three cities. I find a positive correlation (synergy) between the stormwater, air quality, and UHI criteria, and a tradeoff between these three criteria and the connectivity criterion. This is not surprising since those areas with more "connected" vegetated areas should have less impervious areas, reduced air pollution levels, and be cooler. Percent impervious surface is often used as an indicator of UHI, so we would expect the stormwater criterion and UHI criterion to be correlated (Yuan and Bauer 2007).

Other relationships are not consistent across the cities. Stormwater and social vulnerability are positively correlated in LA and Manila, but not in NYC. In both NYC and LA there seems to be a tradeoff between access to green space and air quality. In NYC, I also find weak evidence for a tradeoff between access to green space and UHI. This may be because densely populated Manhattan is built around Central Park, putting most residents there in close proximity to green space. While there is some evidence of a synergy between SoVI and UHI in Manila and to a lesser extent LA, we see a negative correlation in NYC. More in-depth field research and closer study of specific neighborhoods in each of these cities is likely needed to understand these differences.

Overall, the results suggest that it may be possible to site green infrastructure in high priority areas for stormwater management, air quality, and UHI simultaneously. Trying to also prioritize socially vulnerable neighborhoods, those with less access to parks, or expanding and connecting existing habitat may be more problematic. The existence of these tradeoffs suggests that decision-makers should evaluate local priorities as part of a strategic planning process.

3.2 Local priorities and mapping green infrastructure hotspots

Expert stakeholders in the three cities appear to have different priorities with respect to the benefits of green infrastructure. Table 2 presents aggregated survey results of the importance of model criteria for each city. Interestingly, the ordering is only completely consistent across the rating, ranking, and pair-wise comparison questions for LA, and this is the city with the fewest respondents. Nevertheless, there still seems to be some coherent prioritization patterns in NYC and Manila. This becomes clear when one looks more closely at the means (for the 'rating' question a higher score indicates a criterion is seen as more important, whereas for the 'ranking' question a lower score signifies that a criterion is more important) and weights (higher is more important) generated from the pair-wise comparison question. For example, in NYC, managing stormwater is identified as much more important than the other criteria, which are all quite close together. In Manila, the stormwater and air quality benefits were given almost equal priority.

Consistent with other studies (Meerow and Newell 2017, Newell *et al* 2013), stormwater was considered one of the most important benefits in all three cities. The other benefits varied. This may be because green infrastructure has been specifically promoted by influential institutions like the U.S. EPA as a stormwater management approach (U.S. EPA 2017). NYC's green infrastructure plan, for example, lays out specific goals related to improving water quality and managing runoff, while the other desired "sustainability benefits" are not as well defined (PLANYC 2010, p 2). Reducing social vulnerability was deemed most important in LA, but slightly less so in NYC and Manila. Air quality benefits were seen as very important in Manila, but not in NYC or LA. Increasing landscape connectivity was seen as one of the least important criteria, perhaps suggesting that stakeholders are more interested in social benefits than more indirect ecological services of green infrastructure.

Figure 6 shows hotspots for green infrastructure when criteria are weighted and combined (for comparison, combined results without stakeholder weights are presented in Appendix D). We can see, for example, areas of high need for green infrastructure in the Bronx and in Queens and Brooklyn around Newtown Creek in NYC, in the Southeast and Central part of LA, and in some of the older, densely populated western neighborhoods of the City of Manila (see these areas highlighted in Appendix E).

The standard deviations in survey responses (Table 2) show that priorities differ and this survey represents a single snapshot in time and a limited sample. In contrast, the web-based tool (Figure 6) allows anyone to enter their own weights on a scale from one to ten using sliders for each of the six criteria and then press a button to immediately visualize the combined and weighted responses over a street, aerial, or terrain map. Users can zoom in to particular areas of interest and switch between different criterion layers or the combined results. This allows more flexibility and encourages data and scenario exploration.

Table 2 Stakeholder Survey Results: Aggregated survey responses from stakeholders in each city for questions asking them to rate, rank, and individually compare (using pair-wise comparisons) the importance of the six GISP model criteria for green infrastructure siting. *Note*: 'Rank order' reflects the ordinal importance of the criteria (1 being most important).

City	New York (N=28)			Los Angeles (N=6)			Manila (N=19)		
Rating Question									
	Rank order	**Mean**	**Standard deviation**	**Rank order**	**Mean**	**Standard deviation**	**Rank order**	**Mean**	**Standard deviation**
Stormwater	1	4.71	0.66	2	4.50	0.55	2	4.53	0.84
Sovi	3	4.18	1.16	1	4.83	0.41	3	4.21	0.92
Green space	5	4.07	0.86	3	4.00	0.63	4	4.11	0.74
UHI	4	4.14	0.76	4	3.83	0.41	5	4.05	0.91
Air quality	2	4.29	0.76	5	3.67	1.03	1	4.58	0.51
Connectivity	6	3.86	0.93	6	3.50	1.05	5	4.05	1.08
Ranking Question									
	Rank order	**Mean**	**Standard deviation**	**Rank order**	**Mean**	**Standard deviation**	**Rank order**	**Mean**	**Standard deviation**
Stormwater	1	1.71	1.33	2	1.67	0.82	1	2.55	1.75
Sovi	2	3.25	1.80	1	1.50	0.55	5	4.00	1.41
Green space	4	3.75	1.55	3	3.67	0.82	3	3.82	1.54
UHI	5	3.93	1.15	4	4.17	1.47	4	3.45	2.02
Air quality	3	3.54	1.43	5	4.50	1.05	2	2.45	1.13
Connectivity	6	4.82	1.39	6	5.50	0.84	6	4.60	1.51
Pair-wise comparison Question									
	Rank order	**Weight**		**Rank order**	**Weight**		**Rank order**	**Weight**	
Stormwater	1	0.295		2	0.277		1	0.227	
Sovi	3	0.166		1	0.337		4	0.168	
Green space	5	0.122		3	0.125		3	0.169	
UHI	2	0.171		4	0.099		5	0.120	
Air quality	4	0.148		5	0.097		2	0.211	
Connectivity	6	0.096		6	0.064		6	0.105	

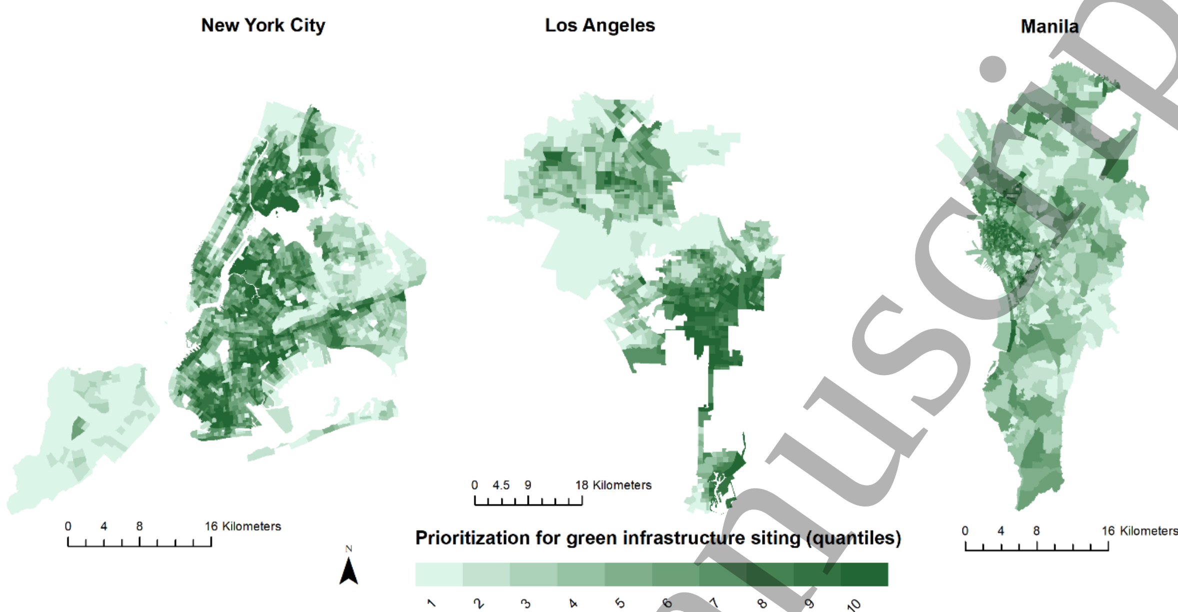

Figure 5 Hotspots for green infrastructure siting in New York, Los Angeles, and Manila: Six criteria combined and weighted using pair-wise comparison survey results.

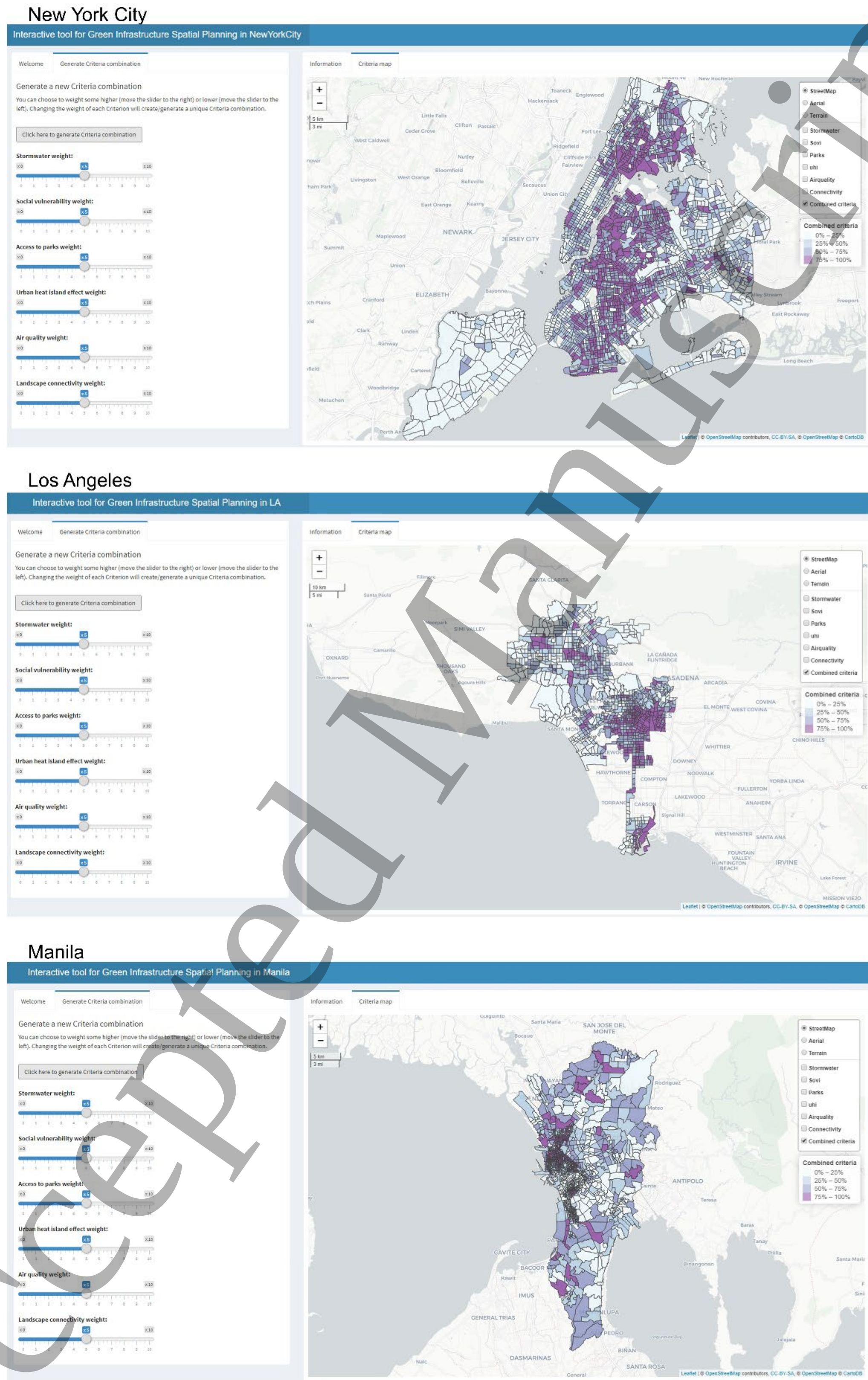

Figure 6 Screenshots of web-based tools for the three cities (www.gispmodel.com)

4. Discussion and conclusion

NYC, LA, and Manila represent three very different coastal megacities. Yet in all three cities there are ongoing efforts to expand green infrastructure and urban vegetation to enhance sustainability and resilience. This is part of a broader trend, as a growing number of scholars, organizations, and governments are promoting the multiple benefits of green infrastructure (Hansen *et al* 2019, Prudencio and Null 2018). The GISP model was developed as a city-wide approach for strategically planning green infrastructure investments based on local priorities and where multiple benefits are needed most, and helps to uncover potential spatial tradeoff and synergy patterns between planning priorities (Meerow and Newell 2017). Extending the GISP model for the first time to compare cities reveals a number of interesting findings. First, it shows that it is possible to develop the model for very different cities, although it was much more difficult to acquire data at a sufficiently fine scale for Manila, and the results should be interpreted with caution. Second, while different data sources were used for the cities, there are several consistent synergy and tradeoff patterns (Figure 4). I identify spatial synergies between stormwater, UHI, and air quality benefit criteria, and a tradeoff between these criteria and increasing landscape connectivity. The same was also true in the initial Detroit model (Meerow and Newell 2017). This is promising, because it suggests that even if stormwater continues to be a major focus of green infrastructure investments, and if areas with high imperviousness are prioritized, developments may also help to address UHI problems and air pollution. In contrast, planning focused on stormwater would not necessarily capture areas of relative park poverty, for example, although increasing access to green space was seen as a somewhat important goal in all three cities. Similarly, stakeholder surveys indicated that stormwater and social vulnerability were both important criteria for green infrastructure siting in NYC and LA, thus it is potentially problematic that the two criteria were not positively correlated in NYC, and only weakly so in

LA. Third, survey results suggest that expert stakeholders see certain green infrastructure benefits as more important in some cities than others (Table 2). Comparisons should be made with caution, however, since the number and institutional affiliation of survey respondents is very different across the three cities (Appendix B).

While the stakeholders I interviewed and surveyed for this study saw practical value in the GISP modeling approach, there are some limitations. First, the model is constrained by data availability. It proved difficult to find comparable datasets for all three cities, especially Manila. For example, the access to green space and air quality indicators used for Manila are different from those used for LA and NYC. The differences in the data used for the Manila model, combined with the fact that Manila, and the Philippines more broadly, is very different from LA or NYC in the U.S., limits the comparative claims that can be made about tradeoff and synergy patterns across all three cities. Temporal inconsistencies in the different datasets (e.g. 2010 SoVI versus 2016/2017 land surface temperature data) may also influence tradeoff or synergy patterns within cities. The model's accuracy depends on the underlying datasets, which are likely imperfect. I also acquired data from a wide variety of sources, which makes it difficult to validate its accuracy. Ultimately, there is a tradeoff between using indicators based on data that is widely available and easily replicated versus data that is highly customized and has been ground-truthed.

The unit of analysis (the census tract and barangay) also limit the model's utility. While census tracts are commonly used in studies (such as social vulnerability indices), each tract represents an average of 4000 residents, so there is likely variability within them. Additionally, census tracts are unrelated to the scales at which governance or planning occurs. Barangays do represent the smallest local government unit in the Philippines, but their population varies even more than US census tracts – the largest in Manila has nearly 250,000 residents (Philippine Statistics Authority 2016).

Despite these limitations, the GISP model, particularly the novel web-based tool (Figure 6), has the potential to inform more strategic green infrastructure spatial planning to enhance social and ecological resilience. NYC and LA already have ambitious plans to expand green infrastructure with explicit multifunctionality aims, and Manila is rapidly developing and is looking for ways to do so in a greener and more resilient way. To maximize limited green infrastructure investments, these cities could focus in on neighborhoods identified by the model as high priority (Figure 5). Decision-makers can also use the web-based tool (Figure 6) to explore in real time how prioritizing different criteria changes priority neighborhoods and to identify potential hotspots across the city for the suite of green infrastructure benefits they see as most important. The GISP model could be used as an initial step in developing a city-wide green infrastructure vision plan or identifying areas for detailed suitability assessments. These finer scale analyses would identify specific sites within modeled priority areas for green infrastructure development as well as appropriate technologies and designs based on land use, cost, and other important contextual factors (Georgescu *et al* 2015).

Finally, the flexible modeling approach could be applied to virtually any city worldwide that is investing in multifunctional green space, helping them to plan more strategically for locally desired outcomes. Many of the datasets used here are widely available (e.g. remotely sensed images, Open Street Map). Different model criteria and specific indicators (e.g. air temperature or air quality monitoring data) could also be substituted or added to refine the accuracy of the results and adjust the model to cities' unique social or geophysical contexts.

Future applications of the model to additional cities can also further validate the generalizability of the ecosystem service synergy and tradeoff patterns identified in this paper.

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Data availability statement
The data that support the findings of this study are openly available at https://doi.org/10.7910/DVN/UVHZGJ.

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