Water Resources Research

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Key Points:
- An agent model explores the impacts of NYC's current green infrastructure policy and an alternative that prioritizes socioeconomic goals
- NYC can manage more stormwater if GI siting decisions align with broader community preferences and aren't confined by sewershed boundaries
- Multifunctional GI siting captures more stormwater and provides more socioeconomic value than siting based on stormwater capture rates alone

Supporting Information:
- Supporting Information S1

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Exploring the Long-Term Economic and Social Impact of Green Infrastructure in New York City

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Abstract Across the world, cities are spending billions of dollars to manage urban runoff through decentralized green infrastructure (GI). This research uses an agent-based model to explore some of the physical, social, and economic consequences of one such urban GI programs. Using the Bronx, NY, as a case study, two alternative approaches to GI application are compared. The first (Model 1) mimics NYC's current GI program by opportunistically selecting sites for GI within the city's priority combined sewer watersheds; the second (Model 2) features a more spatially flexible approach to GI siting, in which the city attempts to maximize opportunities for co-benefits within the geographic areas considered in Model 1. The effects of both approaches, measured in terms of stormwater captured and co-benefits (e.g., carbon sequestered) provided, are tracked over 20-year simulations. While both models suggest it will be difficult to meet the citywide stormwater capture goals (managing the first 2.5 cm of rainfall from 10% of impervious surfaces) in the Bronx solely through public investment in GI, Model 2 shows that by integrating GI with other city initiatives (e.g., sustainability goals and resilience planning), synergistic outcomes are possible. Specifically, Model 2 produces stormwater capture rates comparable to those obtained under Model 1, but these rates are accompanied by elevated co-benefits for Bronx communities. The results are discussed in the context of future GI policy development in NYC.

1. Introduction

In many urban sewer systems, a single-pipe network is used to convey wastewater and stormwater to treatment plants. These systems can overflow or backup during wet weather when the flow exceeds the network's conveyance capacity, resulting in the discharge of untreated wastewater to local waterways and significantly reduced water quality (New York City Department of Environmental Protection [NYC DEP], 2016a; NYC, 2008). When wastewater and stormwater are conveyed in separate piping systems, runoff can still contaminate waterways with trash, bacteria, heavy metals, oil, and other pollutants picked up in the urban environment (NYC DEP, 2016b). To address these problems and improve water quality, many U.S. cities (City of Toronto [COT], 2013, NYC DEP, 2010, Philadelphia Water Department [PWD], 2011, Sewage and Water Board of New Orleans [SWB NO], 2014) have committed billions of dollars toward green infrastructure (GI). For example, New York City plans to spend $1.4 billion on GI by 2030, with a goal of capturing the first 2.5 cm of stormwater from 10% of the impervious surfaces in combined sewer districts (NYC DEP, 2010).

GI sites utilize soil, vegetation, and other natural features to retain, detain, and infiltrate urban runoff, diverting it from engineered collection systems. These processes help treat stormwater at the source, reducing pollutant loads, replenishing soil moisture, recharging aquifers, and mitigating local flooding (Narayan et al., 2016; New York State Sea Level Rise (NYS SLR) Task Force, 2010; Prudencio & Null, 2018; Stoner & Giles, 2011; Temmerman et al., 2013; Wilks, 2011). GI investments include both natural and manmade “green” (vegetated or soil-covered) or “blue” (water-covered) spaces. This research specifically focuses on smaller-scale, stormwater-focused GI sites, such as parks, green roofs, bioswales, street trees, community gardens, and permeable pavers (Jones & Somper, 2014; Prudencio & Null, 2018).

Although primarily implemented as a means of stormwater management, GI can provide many other ecosystem services (ES), including reductions in the urban heat island, improved mental and physical health, food production, better air quality, a greater sense of place, and global climate regulation through carbon sequestration (Alves et al., 2019; Barnhill & Smardon, 2012; de Sousa et al., 2012; Groenewegen et al., 2006; Lafortezza et al., 2013; Lovell & Taylor, 2013; Meerow & Newell, 2017;

Mell et al., 2013; Miller & Montalto, 2019; Prudencio & Null, 2018; Siedlarczyk et al., 2019; Stratus Consulting, 2009; Tzoulas et al., 2007). Some studies have explored the ability of GI networks to provide isolated ES (e.g., Jayasooriya & Ng, 2014; Wang et al., 2014). Others have investigated the ability of a single GI type to provide multiple services (e.g., Loomis et al., 2000; Netusil et al., 2014), including Phillips's (2011) assessment of urban trees in Corvallis, Oregon. Broader attempts have also tried to quantify the full range of ES that can emerge in an urban landscape as cities implement multiple forms of GI over space and time (e.g., Alves et al., 2019; Christin et al., 2014; Elmqvist et al., 2015; Gill et al., 2007; Meerow & Newell, 2017; Prudencio & Null, 2018; Zhan & Chui, 2016). Overwhelmingly, prior studies suggest that GI has a favorable benefit-cost ratio and provides many valuable co-benefits to urban communities. However, gaps remain in our ability to quantify the full range of ES provided by GI, hindering our ability to evaluate the long-term effects of municipal GI programs.

A comprehensive evaluation of municipal GI programs is complex because GI implementation involves multiple actors, whose actions span across physical, social, and institutional domains. Oftentimes, only isolated pilot-scale measurements focused on a single co-benefit are available, making detailed, multidisciplinary observations of widespread GI systems impossible (Prudencio & Null, 2018; Young, 2011). Even if large-scale observations were available, approaches to GI implementation vary widely across cities (COT, 2013; NYC DEP, 2010; PWD, 2011; SWB NO, 2014; Young, 2011), and co-benefits, particularly those related to cultural services, are dependent upon local physical, socioeconomic, and climatological characteristics (Loder, 2014; Prudencio & Null, 2018).

Although a citywide, controlled experiment of new GI typologies or policies would be prohibitively expensive and the effects irreversible (Ghaffarzadegan et al., 2010), models can help predict the emergence of spatiotemporal benefits of a GI program. Despite this, many off-the-shelf GI models only consider GI's hydrologic and hydraulic functionality (e.g., the EPA's Stormwater Management Model [SWMM] or Hydrological System Program—FORTRAN [HSPF]; GreenPlan-IT; and MIKE-Urban); explore program costs (e.g., the EPA's System for Urban Stormwater Treatment and Analysis IntegratioN [SUSTAIN] or LIDRA); or calculate the ES available from a single GI type (e.g., the USDA Forest Service's iTree ECO). However, in the last decade, there has been a shift away from single-issue modeling efforts and a push toward more high-level, integrated urban water system models (e.g., UrbanBEATS, Multifunctional Landscape Assessment Tool [MLAT], Green Infrastructure Spatial Planning [GISP]) (Bach et al., 2014; Lovell, 2010; Meerow & Newell, 2017). Agent-based models (ABMs) are one such tool and enable users to quantify the availability of multiple ES from a diverse portfolio of GI over space and time.

ABMs are tools for analyzing multidisciplinary, multiactor problems (Nikolic & Dijkema, 2010). They simulate complex physical and social dynamics concurrently (Grimm et al., 2010), with outcomes that emerge from interactions between agents and between agents and their environment (Macal & North, 2010; Railsback & Grimm, 2012). ABMs are also important planning tools that can forecast the effects of new policy decisions and compare alternative solutions to a problem (Berger et al., 2006; Ghaffarzadegan et al., 2010; Kandiah et al., 2019; Levy et al., 2016; Matthews et al., 2007; Montalto et al., 2013; Morelle et al., 2019; Zidar et al., 2017). Berger et al. (2006) determined that ABMs can be particularly useful in studying small-scale infrastructure decisions, including GI. As such, ABMs are a growing tool in the field of sociohydrology to study complex, coupled human and water systems (Konar et al., 2019), though examples are still limited. Prior models have explored natural resource policies and decision-making, for example, modeling local water use (Becu et al., 2003; Berger et al., 2006; Kandiah et al., 2019) and overharvesting of community resources (Andersen et al., 2015; Jager & Mosler, 2007), and studied the links between human behavior and biophysical processes, for example, predicting the effect of household fuel use on deforestation and habitat (An et al., 2005; Matthews et al., 2007). More recently, researchers have used ABMs to study GI implementation rates (Castonguay et al., 2016; Montalto et al., 2013; Zidar et al., 2017) and to understand how policy decisions affect co-benefits (Chen et al., 2012; Morelle et al., 2019). However, few researchers have used ABMs to examine GI policy, implementation, and co-benefits simultaneously (Castonguay et al., 2016) as an integrated urban water system model (Bach et al., 2014).

1.1. Purpose and Goals

To our knowledge, a detailed simulation of the multiple benefits of NYC's GI program over space and time has not yet been attempted, though its impact on combined sewer discharges has (NYC DEP, 2016b). This research attempts to fill that gap by quantifying some of the co-benefits GI can provide to local communities alongside stormwater management goals. It is directly preceded by Miller and Montalto (2019), which quantified the local perceived, nonmonetary value of ES from GI in NYC, and a continuation of the researchers' efforts to evaluate the multidisciplinary benefits of GI in NYC.

This research uses an ABM to simulate the spatiotemporal emergence of GI in NYC. Other researchers have explored similar topics in other urban landscapes. For example, Montalto et al. (2013) used an ABM to explore the voluntary adoption of GI in a Philadelphia neighborhood when homeowners are given incentives to install green roofs or rain gardens, and Lim (2018) studied the voluntary adoption of GI by Washington, D.C., residents over a 6-year period. Both papers highlight the importance of resident perspectives and behavior on a “bottom-up” approach to GI development. However, unlike these earlier efforts, this paper focuses on a “top-down” approach to GI development. Our ABM explores how GI driven by institutional decisions and initiatives can affect the availability of ES over space and time and what social and economic impacts those services may have on local communities.

The ABM discussed in this paper was built in NetLogo (Wilensky, 1999) and examines the long-term impacts of a top-down GI program in the Bronx, NY. Ensemble runs simulate future conditions under two different GI implementation schemes over a 20-year period. The first scenario (Model 1) forecasts the long-term stormwater capture and socioeconomic benefits of NYC's *existing* GI program. Model 1 will provide meaningful insights into the effectiveness of NYC's existing GI program and the overall impact a $1.4 billion GI investment might have on Bronx residents. The second scenario (Model 2) tests whether NYC might achieve more socioeconomic benefits for the same approximate financial and institutional investment by preferentially placing GI on blocks with the greatest need for co-benefits. This siting technique follows the precedent set by MillionTreesNYC (Campbell, 2014; Lu et al., 2014) and the GISP modeling work done by Meerow and Newell (2017) in Detroit. Just as the “Trees for Public Health” program was an effort to address some of the broader sustainability objectives outlined in PlaNYC (Campbell, 2014; NYC, 2008), Model 2 pilots a method for utilizing the city's GI program to address multiple goals simultaneously, in this case promoting the social value of GI alongside stormwater management. Previous work has suggested that such multifunctional GI planning can produce more socioeconomic and environmental benefits than traditional GI siting techniques, which traditionally focus on a single ES (e.g., stormwater management) (Meerow & Newell, 2017).

The analysis in this paper compares the greening approaches in Model 1 to Model 2. Specifically, we are interested in whether Model 2's programmatic integration manages stormwater more effectively than Model 1 while simultaneously filling other urban ES gaps (Zidar et al., 2017) in ways that New Yorkers can recognize (Miller & Montalto, 2019).

2. Materials and Methods

This section describes the study site and model development. ABMs are traditionally presented using the ODD (Overview, Design concepts, Details) protocol (Grimm et al., 2006, 2010; Polhill et al., 2008; Railsback & Grimm, 2012). Because of space limitations, only the key model elements are discussed below, and the full ODD protocol is included in the Supporting Information.

2.1. Study Area

This model simulates GI implementation in an approximately 53 km^2 study area surrounding the Bronx River. This region includes portions of four combined sewer tributary areas—the Bronx River Watershed, Hutchinson River Watershed, Westchester Creek Watershed, and the East River/Open Water tributary areas (Figure 1). The relative portions of each watershed included in the model, along with their respective greening targets, are shown in Table 1. Combined, the study area includes 3,147 ha of impervious surfaces. Based on NYC's goal of greening 10% of impervious surfaces in all combined sewersheds, the study area has a target greening rate of 315 ha by 2030. Given that not all watersheds are completely contained within the study area, model results are discussed cumulatively and not by watershed.

2.2. Background Research

ABM predictions are limited by the randomness associated with agent decisions (Valbuena et al., 2009). However, including stakeholders in model construction, as was done here, can address this shortcoming (Valbuena et al., 2009). A variety of empirical methods (e.g., expert knowledge, interviews, and surveys)

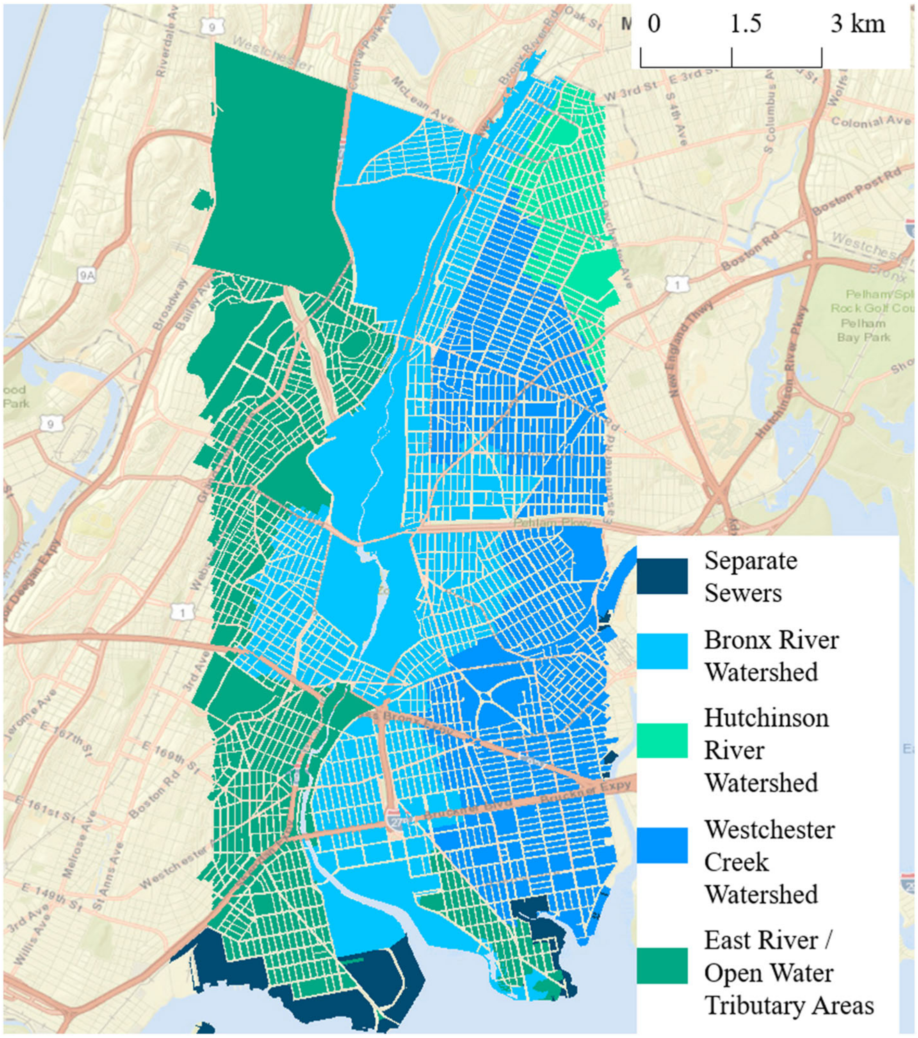

Figure 1. Location of the study area within the Bronx, NY, and of the four combined sewersheds modeled in this research. The dark blue areas represent separate sewer areas that were not subject to greening in either Model 1 or Model 2. The base map for this figure is credited to Esri (2009).

were used to select agents and assign agent attributes and behaviors (Levy et al., 2016; Smajgl et al., 2011). Model decisions and greening practices were primarily determined through semistructured interviews with 35 practitioners of NYC's GI program; interviewees worked for the city, for state and federal overseers of NYC's GI program, in private industry, at state and federal nonprofits engaged with NYC's GI program, and for GI-based community groups in the Bronx. Interviewees offered details into what types of GI to

Table 1
Impervious Surface Targets for Study Area (NYC DEP, 2016c)

Watershed	Total impervious area in the watershed (ha)	Total impervious area included in the model (ha)	Percentage of Total watershed included in the model	10% greening target for the model (ha)	Estimated watershed spending in the model ($, in millions)
Bronx River	943	943	100	94	119
Hutchinson River	456	246	54	25	31
Westchester Creek	1,408	824	59	83	105
East River/Open Waters	16,644	1,133	7	113	28
Total	19,452	3,147	16	315	283

Table 2
Relationship Between Passive Agent Classes and Active Agents

		Active agents								
		DEP	DOE	DPR	DOT	NYCHA	TPL	Mayor's office	Government land owner/operator (e.g., NYPL)	Private property owners
Passive agent classes	Right-of-Way	X			X					
	Schools	X	X				X			
	Public Housing	X				X				
	Other Public Properties	X							X	
	Parkland & Playgrounds	X		X				X		
	Private Properties	X								X

Note. See section 2.3 for the definition of acronyms.

include in the model, as well as where and how each GI type should be implemented. A prepared list of questions was used to guide the interviews, but conversations often deviated to obtain more details from participants (Travaline et al., 2015). A complete list of guiding questions is provided in the Supporting Information. To determine the final design of the model, the information gleaned through semistructured interviews was supplemented with publicly available resources, including NYC's annual GI reports (NYC DEP, 2010, 2012, 2013, 2014, 2015, 2016a, 2016b, 2016c, 2017, 2018, 2019).

2.3. Agents

The models discussed in this paper feature both active and passive agents. The active agents are all the NYC stakeholders and organizations that collaboratively make decisions which affect land use and GI development on publicly and privately owned land parcels throughout the city. They set funding priorities, determine which GI opportunities are available at different times and places, and limit how many GI installations are added each year. Active agents include the Department of Environmental Protection (DEP); the Department of Energy (DOE); the Department of Parks and Recreation (DPR); the Department of Transportation (DOT); the New York City Housing Authority (NYCHA); the Trust for Public Land (TPL); the Mayor's Office; other government landowners and operators, such as the New York Public Library (NYPL); and private property owners.

In contrast, passive agents represent the land parcels (e.g., publicly or privately owned buildings) whose qualities and traits (e.g., perviousness) evolve depending on the actions and decisions of active agents. To simplify the model designs, passive agents were organized into six unique “passive agent classes” based on land use: Right-of-Way, which includes street and sidewalk segments; Schools; Public Housing; Other Public Properties; Parkland & Playgrounds; and Private Properties (Table 2). Passive agents within each class—in other words, the individual land parcels (e.g., buildings and street segments) that share similar physical characteristics—are subject to similar greening strategies and are influenced by the same active agents. Table 2 shows which active agents affect each passive agent class.

Passive agent classes are exposed to unique GI decision pathways, each of which aligns to a specific initiative in NYC's GI program. These pathways represent the collaborative decisions of active agents and spark new GI installations. Although passive agents within the same class are candidates for the same types of GI (e.g., permeable pavement and rain gardens), active agents may assign them to different decision pathways based on the passive agent's location, institutional limits, global limits (e.g., availability of capital funds), and time constraints. It is also possible that passive agents within different classes receive similar GI technologies despite following unique decision pathways (Valbuena et al., 2009). For example, one “Parkland & Playgrounds” agent and one “Schools” agent may both receive permeable pavement around basketball courts, while a second “Parkland & Playgrounds” agent may receive a rain garden and no permeable pavement at all.

Table 3 lists the six passive agent classes, their available GI decision pathways, and the limitations (both physical and institutional) associated with each. These limitations are based on observed implementation challenges between 2010 and 2016 and interviews with NYC GI practitioners. Table 3 also displays when each class is exposed to each GI decision pathway and the construction period associated with each GI

Table 3
Description of Passive Agent Classes Included in the Model

Passive agent class	Available GI decision pathways	Limitations	Years called	Construction period	Funding priority
Right-of-Way	Bioswales, Trees	• Limited to ~20% of nonhighway streets in priority sewersheds and a maximum of 2 sewersheds/year	Years ≥ 4	8 quarters	4
	Permeable Pavement	Limited to nonhighway street segments being repaved each year (max 100/year) • Only 20% of streets meet geotechnical requirements	Years > 8	8 quarters	8
Schools	Permeable Pavement/ Playgrounds, Community Gardens, Rain Barrels, Trees	• Limited to a maximum of 3/year • Limited to playgrounds between 0.4 and 0.8 ha in neighborhoods with the highest under-18 populations	Years 3–12	6 quarters	1
		• Limited to playgrounds in priority sewersheds • The maximum implementation rate is 36/year among all affected agent classes	Years ≥ 5	16 quarters	7
Public Housing	Rain Gardens, Trees	• Limited to priority sewersheds • The maximum implementation rate is 36/year among all affected agent classes • GI confined to ground level	Years ≥ 5	16 quarters	7
		• Limited to a maximum of 1/year • Limited to the sites with the highest percent imperviousness • GI confined to ground level	Years ≥ 1	8 quarters	5
Other Public Properties	Green Roofs[a], Rain Gardens, Trees, Permeable Pavement	• Limited to priority sewersheds • The maximum implementation rate is 36/year among all affected agent classes	Years ≥ 5	16 quarters	7
Parkland & Playgrounds	Rain Gardens, Permeable Pavement/Playgrounds, Trees, Community Gardens, Rain Barrels	• Limited to priority sewersheds • Limited to a maximum of 10/year • Retrofits limited to 25% of the total park area	Years ≥ 5	16 quarters	6
		• Limited to a maximum greening rate of five parks within Community Parks Initiative Zones (areas with under-resourced parks) every other year	Years 5, 7, 9, and 11	12 quarters	3
Private Properties	Green Roofs[a]	• Limited to a maximum of 3/year • Roof area must be more than 1,000 ft^2	Years ≥ 1	12 quarters	2

Note. Limitations, construction periods, and funding priorities for each GI decision corridor are also listed.
[a] Roofs were stochastically selected as extensive (shallow soils, plant options limited to sedums, grasses, and moss), intensive (deep soils, plants may include trees and shrubs), or semi-intensive (medium soil depth, plants may include sedums, grass, flowers, or shrubs).

investment. The construction periods represent the wait time between project initialization and payment for each GI site and its completion, at which point the site is fully operational, that is, collecting stormwater and providing other co-benefits. Also listed in Table 3 are the funding priorities assigned to each passive agent class. These priorities control the numerical order in which GI decision pathways are called in the model and the order in which capital funds are distributed each year. They reflect the current focus of NYC's GI program and were determined through interviews with NYC GI practitioners.

2.4. Schedule of Decisions

Both Models 1 and 2 are run for a period of 20 years at quarterly time steps. The start of each model run corresponds to the first fiscal quarter of 2010, the year when NYC initiated its GI program. Each simulation ends after the last fiscal quarter of 2030, the target end date for NYC's GI program. Decisions that are common to both models are described in more detail below.

A unique capital budget for each simulation is determined at the beginning of each model run. Capital funding is a global factor in the model, meaning that it affects all active agents and decision-making pathways equally. This funding is only available for the first 15 years of the program, the time frame the city has committed to spending money on GI (NYC DEP, 2017).

During each time step, active agents add GI to different passive agents through one or more GI decision pathways. Active agents green passive agents opportunistically, based on the physical and institutional limits

Table 4
Cost for Implementing the GI Typologies Included in This Model

GI type	Cost	Maximum hydraulic loading ratio	Source(s)
Bioswale	\$2,691/m^2	100:1	NYC Green Infrastructure Co-Benefits Calculator (n.d.)
NYC Green Infrastructure Co-Benefits Calculator (n.d.)	\$2,691/m^2	5:1	
Tree	\$1,650/tree	N/A	New York City Department of Parks and Recreation (NYC DPR) (n.d.)
Green Roof	\$355/m^2 extensive \$474/m^2 semi-intensive \$635/m^2 intensive	1:1	Renner (2017)
Community Garden	\$350/raised bed	1:1	Vermont Community Garden Network (VCGM) (2013)
+Rain Barrel	\$3,750	158 m^2	GrowNYC (2016)
+Rain Barrel with Shade Structure	\$5,750	158 m^2	GrowNYC (2016)
Permeable Pavement/Permeable Playground	\$215/m^2	10:1	NYC Green Infrastructure Co-Benefits Calculator (n.d.)

described in Table 3 and global factors, like the availability of capital funds. The impacts of these opportunistic decisions are emergent properties in each scenario.

Once active agents assign passive agents to a specific GI decision pathway, a number of submodels are called to determine how the new GI installation will operate. First, the size of the new GI site is determined using a pseudo-random number generator called Mersenne Twister (Abrahamson & Wilensky, 2004; Wilensky, 1999). The seed for this generator is different for each passive agent and is based on the maximum area available for greening, a factor determined by property size, existing perviousness, and the agent's class. Then the hydraulic loading ratio (HLR), the ratio of the tributary drainage area to the infiltration area (i.e., the area of the GI site), is similarly probabilistically determined. HLRs are constrained by the size of the GI site and the maximum HLRs listed in Table 4, which derive from observations of NYC's current GI practices. Finally, if there is enough capital funds to cover the cost of the new GI site, construction begins. The cost of implementing various GI practices is shown in Table 4. Funds are distributed to each GI decision pathway according to priorities shown in Table 3. Funding priorities are such that, some years, capital funding may be exhausted before all GI decision pathways are utilized.

Once funded, GI projects then enter their construction period. Only after construction is finished and sites are completed do they start supplying co-benefits and capturing stormwater. In the fourth quarter of each fiscal year, the stormwater capture rates (hectares greened), social value, and economic value of co-benefits are calculated from all passive agents with completed GI sites.

At the end of each model run, the total hectares greened are calculated. Hectares greened represents the area of impervious surfaces managed through GI. The social and economic value of GI is also calculated at the end of each run, per the methodologies described below.

2.5. Social Value of Co-Benefits

In these models, the local social value (LSV) of GI is estimated as the number of people who appreciate nearby GI sites and are positively impacted by their presence. Conceptually, *LSV* gauges the sociocultural value of GI for communities, as opposed to the stormwater capture potential of sites. For this research, *LSV* is defined as the number of residents within a census block who value GI; it is a product of resident preferences and exposure to different GI types.

Resident preferences are represented by empirically derived public value coefficients (PVCs). PVCs are a measure of GI's multifunctionality, as perceived by NYC residents. They derive from surveys (Miller & Montalto, 2019), which asked residents about the ESs they perceive and value from different GI sites. Though Miller and Montalto (2019) considered 22 ESs, for this paper, all PVCs were aggregated into a single score for each GI site. These aggregate PVCs encompass all 22 ESs considered in Miller and Montalto (2019) and represent the perceived multifunctionality of GI by local residents. Aggregate PVCs range from 0, meaning that all surveyed residents perceived no value from all 22 ESs, to 1, in which case all residents perceived value from all 22 ESs. The aggregate PVCs included in this analysis are presented in (Table 5).

Table 5
Aggregate Public Value Coefficients (PVCs) Determined Through Surveys With GI Practitioners and Residents of NYC (Miller & Montalto, 2019)

GI type	Aggregate PVCs
Right-of-Way Bioswales	0.52
Green Roofs	0.33
Trees	0.46
Community Gardens	0.50
Rain Gardens	0.52
Permeable Playgrounds	0.25
Public Parks	0.57

Exposure is represented as a population and is a function of the passive agent class into which each GI site is placed. In other words, exposure is the population of New Yorkers living within the immediate vicinity of each new GI parcel. GI added to Schools or Parkland & Playgrounds passive agents are experienced (and valued) by people living within a 0.40 km radius (Donahue, 2011). Other passive agent classes (e.g., Right-of-Way, Other Public Properties, or Private Property) only have an exposure area equal to their census block. The larger exposure radius for Schools and Parkland & Playgrounds agents reflects the fact that people are often willing to travel to visit parks or playgrounds (Donahue, 2011; Giles-Corti et al., 2005).

LSV is measured at the census block scale as a weighted average of people pleased by different GI interventions, Equation 3.1.

$$LSV = \frac{(Pop_1 {*} PVC_1) + (Pop_2 {*} PVC_2) + \ldots(Pop_7 {*} PVC_7)}{7} \tag{3.1}$$

where Pop_n represents the number of residents exposed to GI type n, and PVC_n represents the PVC associated with each GI type (Table 5).

At the start of each simulation, and according to Equation 3.1, the *LSV* of the study area is 47,044 people, primarily as a result of the existing parkland. Theoretically, the maximum *LSV* for each census block is equal to its total population (an average of 254 people), a situation that can only be achieved if all residents are exposed to and value all seven GI types considered in this model. However, as Table 5 shows, no GI type is universally valued by NYC residents. For this reason, the actual maximum *LSV* for any census block is approximately 45% of its total population. Given that the study area's total population is 825,538, the maximum achievable *LSV* for the entire study area is 371,492 people.

2.6. Economic Value of Co-Benefits

To measure the economic value of GI, five co-benefits are considered in this study—water regulation (i.e., stormwater management), air quality, global climate regulation, local climate regulation, and esthetic value. These co-benefits were identified as important to NYC through the city's own efforts to quantify the economic impact of individual GI sites and make up the bulk of the city's co-benefits calculation efforts (NYC Green Infrastructure Co-Benefits Calculator, n.d.; NYC DEP, 2012, 2017). The yearly value of these benefits is based on liters of stormwater captured, grams of pollutants removed from the air, grams of carbon sequestered, energy cost savings, and property value increases, respectively (Tables 6 and 7). Annual values were acquired directly through NYC's Green Infrastructure Co-Benefits Calculator (n.d.) and represent the city's unique economic evaluation of GI's co-benefits (Tables 6 and 7). Based on the city's methodology, neither permeable playgrounds nor permeable pavement offers any value beyond stormwater capture. For the purpose of this analysis, economic value is only calculated for new GI sites built as part of the city's GI program; preexisting GIs (e.g., public parks and street trees) were not considered.

2.7. Comparing Models 1 and 2

Figures 2 and 3 outline the schedule of decisions for Models 1 and 2, respectively, with differences between the two models highlighted in the yellow boxes. In general, the two models follow the same schedule of

Table 6
Annual Carbon Storage and Pollutant Removal Rates for Each GI Type Included in This Model (NYC Green Infrastructure Co-Benefits Calculator, n.d.)

GI type	Carbon sequestration (g/year)	Pollutant removal (g/year)			
		O_3	PM10	NO_2	SO_2
Bioswales/Rain Gardens/Community Gardens	71.9	0.22	0.20	0.18	0.10
Green Roofs	30.2	0.25	0.09	0.04	0.24
Trees	3,632/tree	56.1/tree	37.0/tree	37.9/tree	20.8/tree

decisions for all quarters. The only differences affect where GI is built on public properties in Quarter 2. In Model 1, public property retrofits are scattered throughout the study area, affecting a set number of Schoolyard, Public Housing, Other Public Properties, and Parkland & Playgrounds passive agents. In Model 2, the same number of agents are selected for greening, but retrofits are limited to those agents that reside within census blocks that contain the lowest percentage of *LSV*. Similarly, Right-of-Way retrofits are also limited to passive agents in low-*LSV* census blocks in Model 2. By contrast, in Model 1, active agents focus their Right-of-Way greening efforts in one combined sewershed at a time and target Street passive agents purely based on their sewershed location (NYC DEP, 2013).

Models 1 and 2 are compared based on the total hectares greened, the number of *LSV*, and the total economic value of GI produced under each scenario. Independent-samples *t* tests were used to determine if the differences between models were statistically significant.

Table 7
Annual Economic Value for the Five Co-Benefits Considered in This Model (NYC Green Infrastructure Co-Benefits Calculator, n.d.)

Ecosystem service	Economic value
Carbon sequestration	0.0014 ($/g)
Pollutant removal	
O_3	0.010 ($/g)
PM10	0.007 ($/g)
NO_2	0.010 ($/g)
SO_2	0.002 ($/g)
Energy cost savings—Green Roofs	1.94 ($/m^2)
Energy cost savings—Other GI	0.65 ($/m^2)
Property value[a]	1.08 ($/m^2)
Stormwater managed[b]	0.00008 ($/liter captured)

[a] Based on a market value increase of 9% for neighboring properties.
[b] Assumes that 60% of all stormwater captured at the site would otherwise have been treated.

2.8. Calibration

Models 1 and 2 were calibrated to known and expected GI expenditures. Annual budgets for the first 6 years of the simulation were equal to DEP's reported GI spending (NYC DEP, 2017). Funding for the next 9 years was randomly selected by the model, assuming a normal distribution, with a mean and standard deviation determined by the citywide expenses for Years 1 through 6. Since capital funding is reported for the entire city (NYC DEP, 2017), yearly values are multiplied by a scaling factor (0.18) to compensate for the fact that the model area encompasses approximately 18% of the city's total priority sewershed area.

Validating ABMs is notoriously difficult (Levy et al., 2016). In this paper, we attempt to empirically validate Model 1's predictive capacity by comparing the first few years of the simulation against observed greening practices in the Bronx. Because there is no real-world counterpart to Model 2, no empirical validation was possible for the second model. However, both models were subjected to structural validation (Levy et al., 2016). That is, the processes and outcomes of both models were deemed reasonable and plausible by the same stakeholders whose expert opinions informed the model designs.

To empirically validate Model 1, simulation results were compared against the actual greening in the Bronx River Watershed between 2010 and 2016. Specifically, the average hectares greened was compared to the reported hectares greened at Year 6 in the GI program (NYC DEP, 2017). Only the first 6 years of the simulation were considered since this was the best available data at the time the model was created. The results were considered valid if predicted hectares greened were within 10% of the actual hectares greened. Since only portions of the Hutchinson River Watershed, Westchester Creek Watershed, and East River/Open Water sewersheds fall within the study site, hectares greened reported or simulated in these regions were not factored into the validation process.

To validate that Model 1 was creating GI at an appropriate rate, the number of GI sites actually built in the study area between 2010 and 2016 (Rybicka-Kosiec, 2017) was compared to the number of sites predicted by the ABM. Predicted values within 10% of actual construction rates were considered acceptable. The locations of both observed and simulated GI sites were not considered as part of this validation effort.

More information about model calibration and the validation of Model 1 can be found in the Supporting Information.

2.9. Determining the Number of Simulations

Though every effort was made to replicate conditions in the study area, the development of a true-to-life ABM is impractical (Levy et al., 2016; Nikolic & Dijkema, 2010). Additionally, since agent decisions are stochastic, each run results in slightly different outputs, so multiple runs must be performed before any conclusions can be drawn. In general, models should be run as many times as feasible, as each run increases the accuracy of prediction, though there is a point of diminishing returns (Ritter et al., 2011). At a minimum, each model should be run until its results begin to stabilize (Bryne, 2013; Ritter et al., 2011).

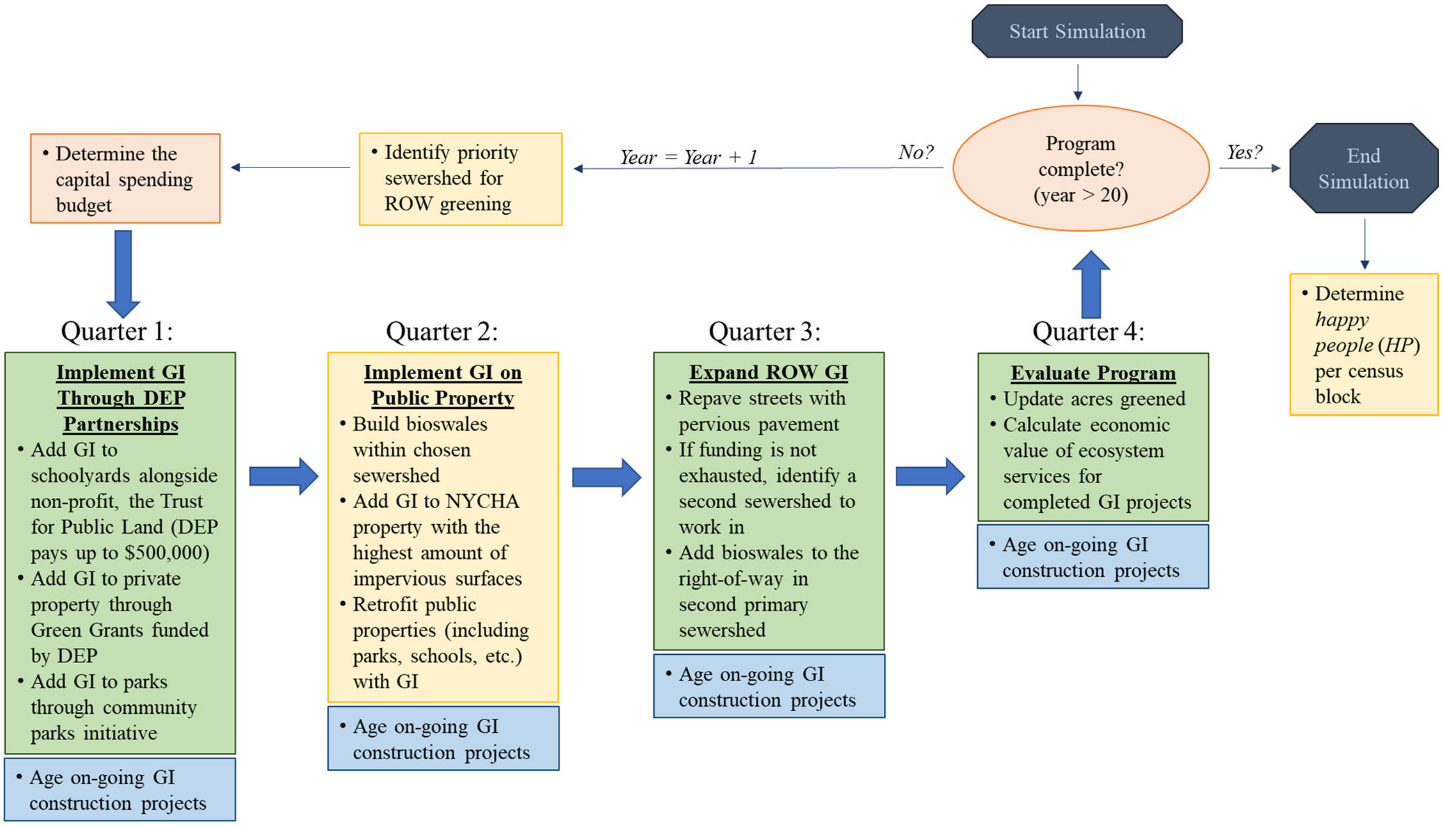

Figure 2. Schedule of decision making for Model 1.

In this application, hectares greened was the output used to evaluate the model's predictive stability. The minimum point of stability was judged graphically by plotting the mean and standard deviation against the number of runs and looking for the point of convergence for each variable (Bryne, 2013). This number was validated using the formula proposed by Ritter et al. (2011):

$$N = \left(\frac{Standard\ Deviation}{SEM}\right)^2 \tag{3.2}$$

where *SEM* is the standard error of the mean. For the purposes of this research, 1.6 was set as the minimum threshold for an acceptable standard error, which signifies that the true mean of hectares greened has a 95% chance of being within ±3.15 ha of the estimated mean. This margin of error, ±3.15 ha, was chosen since it represents 0.1% of the total targeted hectares greened.

The number of trials was also verified using the formula proposed by Bryne (2013):

$$N = \left(\frac{z}{w} * CV\right)^2 \tag{3.3}$$

where z is the value of the standard normal (1.96 for 95% confidence), w is the desired precision measured as the proportion of the mean, and CV is the coefficient of variation (measured as the ratio of the standard deviation to the mean). Using ±3.15 ha as the target margin of error, w is 0.01.

Initially, a total of 1,200 simulations of Model 1 was run to estimate the mean and standard deviation. The minimum number of scenarios was then estimated both graphically and using Equations 3.2 and 3.3. Through this process, it was determined that 750 model runs would produce sufficiently stable model results. Additional details on this process are provided in the Supporting Information.

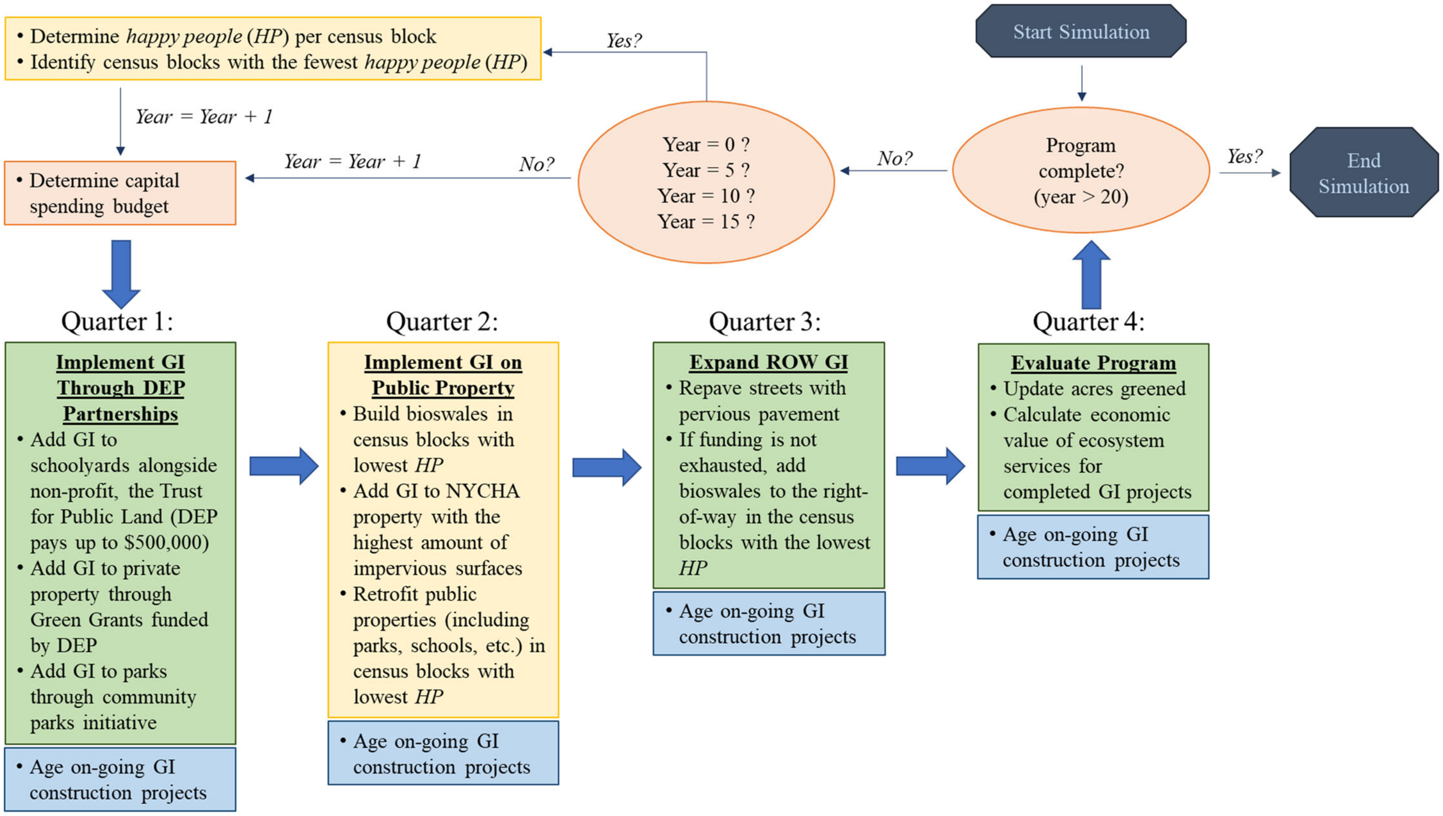

Figure 3. Schedule of decision making for Model 2.

3. Results

3.1. Cumulative Hectares Greened

Model 1 falls short of the targeted stormwater capture rate (315 ha greened), with an average of only 229 ha greened (±22.5 ha) (Figure 4). Out of 750 model runs, only one run exceeded 315 ha. Under Model 2, the city manages slightly more stormwater, with an average of 254 ha greened (±22.4 ha). This represents a 10%

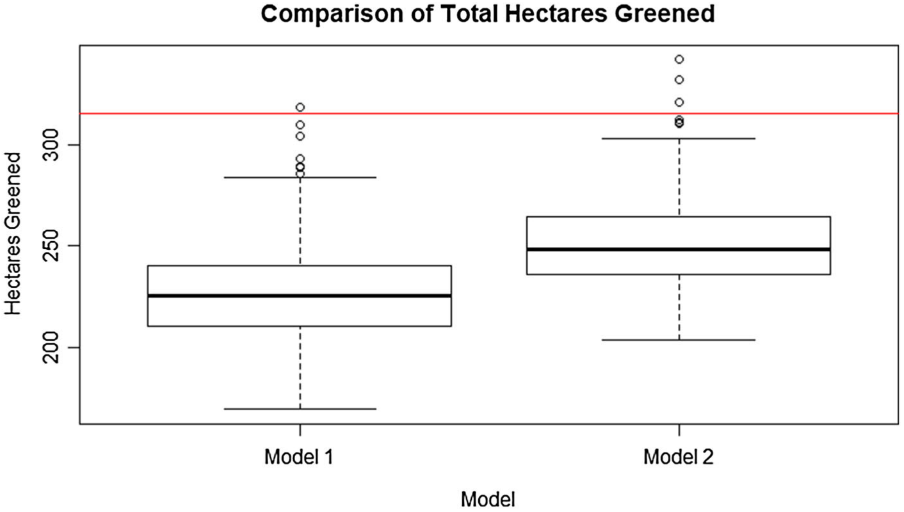

Figure 4. Total hectares greened for each modeling scenario. The redline represents the target acres greened for the study area (315 ha).

statistically significant improvement over Model 1 ($p \leq 0.0001$). However, this rate of greening is still below the city's target for the study area (Figure 5). Out of 750 model runs, Model 2 exceeds the target greening rate for the entire study area only seven times.

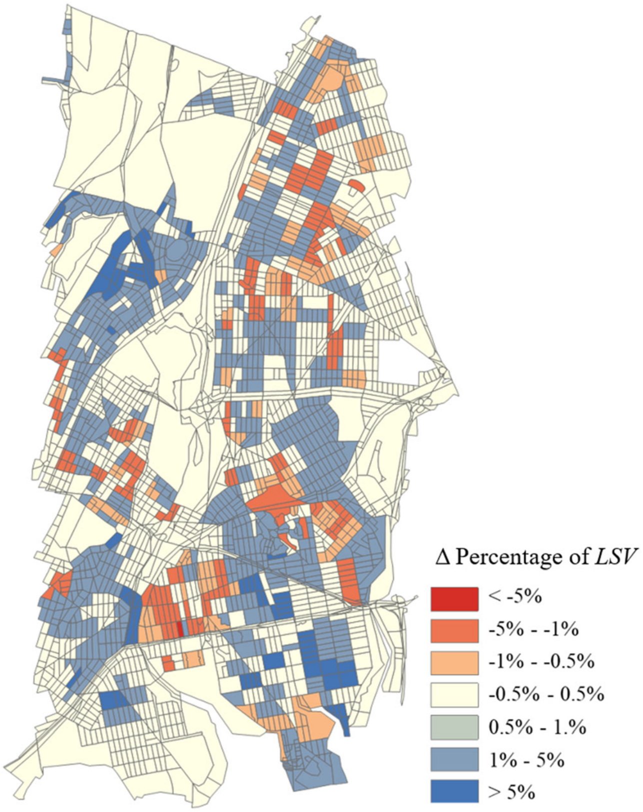

Figure 5. Change in LSV between Models 1 and 2. Census blocks in reds and oranges represent areas where fewer people valued GI under Model 2 conditions, while census blocks in blue represent neighborhoods where more people valued GI under Model 2 conditions.

3.2. Greening by GI Type

In general, Model 2 results in slightly more GI sites than Model 1, with an average of 2,963 unique GI projects compared to 2,812 (Table 8); these differences are statistically significant ($p \leq 0.0001$). Both models see similar construction rates for rain gardens, green roofs, community gardens, and permeable playgrounds. However, Model 2 results in significantly more bioswales and trees than Model 1. Model 2 also results in significantly fewer permeable pavement installations than Model 1. However, this decrease is only for the number of unique permeable pavement projects, as Model 2 averages more total hectares of permeable pavement than Model 1 (Table 8).

Under both modeling scenarios, bioswales have the largest HLR of all GI types, a value approximately equal to the median value observed for existing NYC bioswales (NYC DEP, 2016b) (Table 8). Bioswales also manage the largest portion of stormwater, despite accounting for the second smallest total area (Table 8). Permeable playgrounds and permeable pavement come in a distant second and third in terms of stormwater managed but first and second in terms of total area under both Model 1 and Model 2 conditions (Table 8). Trees were exempt from all stormwater calculations; since they primarily occupy space within other GI sites, their contribution to stormwater management is assumed to be negligible compared to the larger GI sites within which they reside. NYC also does not currently calculate or request credit for stormwater managed by trees (NYC DEP, 2017, 2018, 2019).

3.3. Social Value of Co-Benefits

At the end of the 20-year program under Model 1 conditions, *LSV* is equal to 125,322 people. In other words, more than 125,000 New Yorkers will live near and value the new GI construction, or approximately 34% of the study area's maximum cumulative *LSV*. Model 2 predicts that 134,377 Bronx residents will live near and value GI at the end of the city's 20-year GI buildout, or approximately 36% of the maximum *LSV*. This represents a statistically significant improvement over Model 1 ($p \leq 0.0001$). For comparison, if NYC's GI program were not limited by financial and institutional constraints and were able to maximize GI on all physically suitable sites, the total *LSV* would be equal to approximately 165,400, or 45% of the maximum *LSV* (see Supporting Information for calculations).

Table 8
Average Hectares Greened and the Average Hydraulic Loading Ratio for the Six GI Typologies Included in This Model (Trees Are Excluded From Some Calculations)

	Total number		Average hectares of site		Average loading ratio		Average hectares greened	
GI type	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Bioswales	1,136	1,229	7.1	7.7	50.5:1	50.5:1	356.1	387.6
Rain Gardens	103	99	11.3	11.4	3.3:1	3.7:1	36.9	41.9
Green Roofs	52	51	8.2	7.1	1.0:1	1.0:1	8.2	7.1
Trees	1,244	1,326	NA	NA	NA	NA	NA	NA
Community Gardens	1	1	0.3	2.8	1.1:1	1.1:1	0.3	0.3
Permeable Playgrounds	67	73	21.1	23.5	4.1:1	4.2:1	87.3	101.4
Permeable Pavement	110	85	14.0	15.6	5.5:1	5.6:1	76.5	90.2

Table 9
Economic Value of GI's Co-Benefits by Scenario

Scenario	Cumulative value after 20 years (in $ millions)	Annual value at the end of 20 years (in $ millions)
Model 1	$18.7 (±$1.4)	$1.8
Model 2	$19.9 (±$1.3)	$2.0
Maximum GI buildout	$785 (±$50.4)	$43.0

Figure 5 compares how variations in GI placement between Models 1 and 2 translate into differences in total *LSV* and changes in *LSV* at the census block scale. A total of 1,918 census blocks experience a change in *LSV* between Models 1 and 2 (Figure 5). Of these, *LSV* is higher in 1,298 census blocks under Model 2 conditions compared to Model 1. On average, each of these census blocks contains 10 more people who value the new GI sites, for a combined *LSV* increase of 9,055 people. Since each census block has an average population of just over 250, Model 2 results in approximately 5% more *LSV* in each block than Model 1. In contrast, the mean change in *LSV* for the 620 census blocks that lose social value between Models 2 and 1 is only −3 people or less than 1% of the average census block population.

3.4. Economic Value of Co-Benefits

Under Model 1 conditions, the total economic value of co-benefits after 20 years is $18.7 million ± $1.4 million (Table 9 and Figure 6). Figure 6 shows that the total economic value rises slowly at first, before accelerating after 10 years. By the end of the simulation, the study area is receiving approximately $1.8 million in benefits per year. Under Model 2, the total economic value of co-benefits is $19.9 million ± $1.3 million (Table 9 and Figure 6). At the end of Model 2, the city is receiving approximately $2.0 million in benefits per year. For comparison, if NYC's GI program were not limited by financial and institutional constraints and were able to experience a maximum GI buildout (GI on all physically suitable sites), the yearly economic value would be approximately $43 million (see Supporting Information for calculations) (Table 9).

The average total capital expenditures were $281 million ± $5 million for Model 1 and $283 million ± $6 million for Model 2. Both values are within the estimated expenses for the study area and not statistically different.

4. Discussion

4.1. Long-Term Impacts of GI: Stormwater Capture

This ABM suggests that NYC will fall short of its greened area goals in the Bronx, at least under its current approach to GI implementation. Under Model 1 conditions, the city exceeded the target hectares greened (315) only once in 750 simulations, with most runs falling over 60 ha shy. Although Model 2 manages slightly more stormwater, the average hectares greened was still well below the goal.

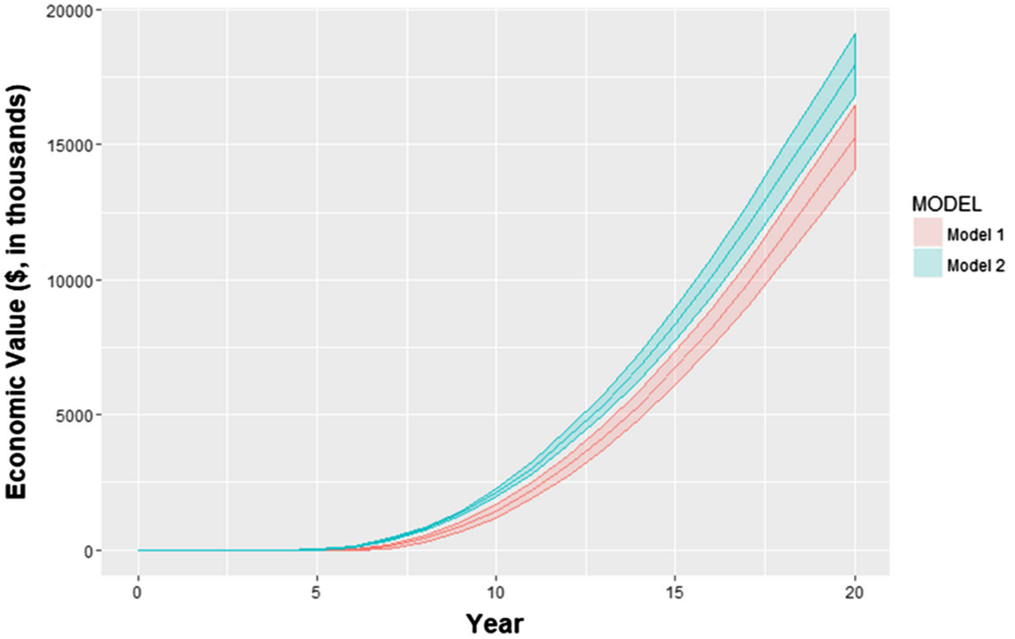

Figure 6. Economic value of GI and its co-benefits over time.

Though the results presented in this paper only apply to a subset of the Bronx, we predict that NYC as a whole may also struggle to capture the first 2.5 cm of runoff from 10% of impervious surfaces. Other NYC neighborhoods and boroughs have different land use patterns than the Bronx and, as a result, will have different GI buildout patterns, which may be more or less effective than what we could simulate for the Bronx. However, many of the institutional, budgetary, and physical limitations that prohibited our models from reaching their targeted hectares greened will still apply in these other neighborhoods and boroughs, suggesting that additional innovations may be needed for NYC to meet its stormwater capture goals.

During background research for this ABM, stakeholders suggested various strategies to increase stormwater capture. Two suggestions—permitting detention (i.e., slow release) from GI sites not suitable for infiltration and capturing runoff from highways—increase the impervious area available for GI, while another—conveying runoff across streets and property lines—would increase the hydraulic loading of existing sites. However, this modeling effort suggests that funding, not the number of available GI sites or their hydraulic load, is the primary limitation to meeting stormwater management goals. Under a maximum buildout scenario in which all publicly owned street segments and land parcels (all non-Private Property passive agents) receive some form of GI regardless of the cost, the city can green nearly 2,023 ha, well beyond the targeted 315 ha for the study area. This finding suggests that by dedicating more funding to GI and investing in institutional capacity (e.g., hiring more staff to build GI each year), the Bronx can come closer to meeting its stormwater capture goals than what appears possible given current GI program funding. Unfortunately, a more nuanced exploration into how capital budgets might affect the GI program was beyond the scope of this paper. However, future adaptations of this ABM could determine exactly how much more financial investment is needed from the city to meet stormwater capture goals on public properties and/or the extent to which incentives for private GI can make up the difference. For example, as of 2019, NYC now mandates green roofs on certain types of private properties (Local Laws 92 and 94 of 2019), but the impact this mandate will have on stormwater capture goals is still unknown and will need to be the subject of a separate investigation.

Assuming the city will not increase its capital investment in GI, private investment may offer the next best opportunity to meet stormwater management goals (New York University Stern Center for Sustainability (NYU Stern) and Natural Resources Defense Council (NRDC), 2017). As far back as 2010, NYC was suggesting that private GI would account for nearly 50% of the city's total investment (NYC DEP, 2010). However, to date, private adoption of GI has been slow. The city partnered with the Natural Resources Defense Council to devise ways of expanding GI onto private property (NYC DEP, 2017; NYU Stern and NRDC, 2017). Regardless of which approach is taken, Gundlach (2017) hints that public approval of and education about GI will be key to encouraging private investment. An approach to GI that addresses the public value of GI, perhaps like the one tested in Model 2, might pair well with other efforts to promote private investment in GI. Future work with this ABM can be used to further explore this topic, including testing different scenarios to encourage GI on private property (e.g., a stormwater fee).

4.2. Long-Term Impacts of GI: Social Value

Under both modeling scenarios, the predicted *LSV* should be considered a conservative, low estimate. This is partly because the aggregate PVC used to calculate *LSV* is a composite of local opinions for 22 different ESs, some of which are significantly more valued than the aggregate PVC would suggest (Miller & Montalto, 2019). *LSV* values are also low because the area of exposure for each GI site was a conservative estimate. For example, the exposure area for Parkland & Playgrounds or Schools agent classes is 0.40 km, though the literature often cites 0.80 km as the distance people will travel to visit parks and playgrounds (Donahue, 2011; Reyes et al., 2014; Wang et al., 2015). Similarly, the exposure area of other GI sites is also small, with installations only impacting people living in their immediate vicinity (the same census block). Conceivably, more people could experience GI in their daily travels around the city. For example, a bioswale near a popular bus stop may be highly valued by residents from far-flung sections of the city, and a green roof may have a greater exposure if it is open to the public (Loder, 2014).

However, it is worth noting that this modeling effort does not consider the disservices associated with GI and therefore cannot calculate the number of New Yorkers who are "unhappy" by its presence. Though both models are predicting over 125,000 residents will value the new GI installations, there is an unknown number of people dissatisfied with the new green spaces within their neighborhoods or negatively affected by them. These citizens might be concerned about flooding, find the new infrastructure unattractive, or fear hidden costs to homeowners, among other worries. This model also does not simulate the number of residents who might be upset during different phases of GI installation, including early construction. Some GI typologies, such as those on schools or playgrounds, could close public facilities for significant periods of time, negatively impacting the community. As such, the actual number of people who value GI is likely to fluctuate over time, depending on the phase of construction and the quality of maintenance after sites are built. Lastly, the aggregate PVC used to calculate *LSV* was determined by surveying NYC's residents about their preferences for different GI types (Miller & Montalto, 2019). However, the results of these surveys only measure current opinions about GI and are not necessarily indicative of past or future sentiments (Robinson et al., 2007). As such, they may not accurately reflect the number of people who will value different GI typologies in Years 10, 15, 20, and beyond. More work with this ABM is necessary to explore these and other temporal anomalies associated with *LSV* and the social value of GI.

While the *LSV* associated with GI is likely to fluctuate over space and time based on the distribution of GI, the quality of sites and their maintenance, changes in neighborhood demographics, changes in public awareness, public education campaigns, and a host of other social factors not considered in this research, it is not the only social impact GI will have. For example, large investments in GI may affect a community's resilience to climate change. Unfortunately, a more nuanced investigation into all aspects of GI's social impacts was beyond the scope of this research and the abilities of this ABM. Despite this, *LSV* does provide a first look at how alternative GI policies, as explored in Models 1 and 2, may have noticeably different impacts on communities and neighborhoods.

4.3. Long-Term Impacts of GI: Economic Value

As calculated here, the economic value of GI is based on specific co-benefits provided by GI sites and the corresponding dollar value of those services, as determined by NYC (NYC Green Infrastructure Co-Benefits Calculator, n.d.; NYC DEP, 2012, 2017). Although this valuation methodology is relatively simple, it provides a useful first look at GI's long-term cost-benefit projections relative to the capital expense of building new GI sites. Some literature has suggested that the economic value of GI's co-benefits (e.g., carbon storage and pollutant removal) can offset the costs of construction and ongoing operations and maintenance (O&M) fees associated with GI sites (Clark et al., 2008; Elmqvist et al., 2015; Vandermeulen et al., 2011; Wolf et al., 2014; Zhan & Chui, 2016). However, this modeling effort suggests that is unlikely. Regardless of which scenario is considered, the economic value of GI's co-benefits falls significantly short of GI construction and maintenance expenses.

Yearly O&M fees for GI are covered by the NYC DEP, which is responsible for maintaining the quality of GI, including keeping sites operating at the highest capacity and esthetically pleasing (NYC DEP, 2019). O&M includes a weekly site visit by DEP employees, who prune, weed, trim plants, remove trash and debris, and clean sediment that can impede the functionality of the site performance (NYC DEP, 2019). Upkeep costs for GI vary by infrastructure type, size, neighborhood, and season (NYC DEP, 2019). However, an initial analysis, based on the type and quantity of GI built and using the maintenance fees provided in the NYC Green Infrastructure Co-Benefits Calculator (n.d.), estimates that annual O&M fees are approximately $4.5 million (Model 1) and $4.8 million (Model 2) at the end of the 20-year simulations.

In both models, the annual upkeep costs of GI outpace the annual economic value derived from GI's co-benefits by a large margin. It should be noted that the estimated annual value of GI's co-benefits is within the range reported by Elmqvist et al. (2015), with an average value of $7,860/ha/year (Model 1) and $7,874/ha/year (Model 2). For these reasons, the payback periods predicted by both Models 1 and 2 are long for infrastructure investment.

NYC is expected to spend a little over $280 million on GI construction in the study area. It will take roughly 160 years to pay back this investment under Model 1 conditions, based on an economic valuation of the five co-benefits considered here (water regulation, improved air quality, global climate regulation, local climate regulation, and esthetic value). At 150 years, the payback period is slightly lower for Model 2. Though many co-benefits were not included in this valuation effort and trees might be expected to provide more value each year as they grow larger (if they had been allowed to grow in the model), the payback period is not likely to be less than 100 years. These findings are in line with the work of Berardi et al. (2014), who also determined the payback period for GI was well over 100 years in rainy climates.

Although this analysis suggests that the economic value of GI's co-benefits is insufficient to fully cover GI's upfront capital expense or its ongoing cost, it does not consider the cost of doing nothing, in which case the city could be fined by the EPA or sued by a third party for failing to meet Clean Water Act standards. Nor does this analysis consider the cost of adding gray infrastructure. Compared to these alternatives, GI is by far the cheaper option (MacMullan & Reich, 2007; NYC DEP, 2010; PWD, 2011; Wang et al., 2013). From this point of view, co-benefits may be considered extra value for the city. Additionally, a more robust analysis of GI's economic value, for example, one that included more co-benefits or one that allowed for more fluctuation in values between GI types and across different neighborhoods, might paint a more favorable view of GI's economic value and improve its triple bottom line.

4.4. Comparing GI Policies

Despite the challenges described above, this paper shows that even small adjustments to NYC's GI program can produce better stormwater rates and more economic and social value. Model 2 produced more hectares greened (254) than Model 1 (229), provided greater economic value, and offered more value to residents. For approximately the same capital expense as Model 1, it yielded more benefits across the board.

The improvements from Model 2 to Model 1 are modest, primarily as a result of two factors. First, the geospatial and physical characteristics of the watersheds do not change between Models 1 and 2, so both scenarios operate under the same physical, financial, and institutional limitations. As a result, the two models built hundreds of similar GI sites under the same constraints and through similar decision pathways. Second, the policy changes between Models 1 and 2 were minor and primarily affected which GI types were prioritized in each neighborhood. These policy changes affected a small number of installations each year, compared to the thousands of GI sites built during each simulation. However, over time, these affected installations resulted in key, but subtle, differences between the stormwater capture rates and the socioeconomic impacts of the two models.

Many of the differences between Models 1 and 2 can be attributed to changes in how bioswales are sited. Both Models 1 and 2 produced more bioswales than any other GI type. This is primarily because bioswales had a relatively high funding priority and relatively few institutional limits. However, there is one institutional limit under Model 1 rules that confined bioswales construction to one combined sewershed per year. This reflects the current NYC GI policy, where the city tries to maximize right-of-way construction in one area at a time and which results in a lot of new bioswales in one sewershed each year. By confining bioswales to a single sewershed at a time, Model 1 limited bioswale construction to a specific area, regardless of the physical capacity of that area to contain new bioswales or the available funding. Under Model 2 rules, the city viewed the study area more holistically and did not confine bioswale construction to a single sewershed each year. Instead, active agents placed bioswales where they could improve social value the most. Since the city was not confined to building bioswales within self-imposed political boundaries (i.e., the boundaries of a single sewershed) each year, it could develop bioswales across multiple sewersheds at once and maximize the funding available for bioswales each year. As a result, Model 2 generally produced more bioswales than Model 1. These additional GI sites captured additional stormwater and provided more socioeconomic value to NYC residents.

Model 2 suggests that if the city considers GI more holistically, such as by targeting gaps in public approval alongside stormwater goals, and focuses less on individual sewershed goals, it might achieve better stormwater capture rates. In practice, the city probably focuses on one sewershed at a time because lumping all geotechnical tests and construction efforts into a confined area saves time and money. A radical new approach to GI would be necessary to overcome these benefits and enable the city to get more from its green spaces.

Comparing the two GI policies modeled here suggests that approaching GI as a multifunctional infrastructure investment, one that is used to address multiple concerns at once (not just stormwater management), might result in more benefits to the city and more value for stakeholders. Both Models 1 and 2 built the same types of GI investments, relied on statistically similar capital budgets, and concentrated new construction in the same combined sewersheds, yet Model 2 was still able to provide more stormwater, economic, and social benefits to the Bronx. This is true despite the fact that Model 2 made only modest changes to Model 1 rules, only altering those that affected the siting of bioswales and other public property retrofits. As a result, increases in economic and social value were similarly modest. However, significantly more innovative siting and design, such as using GI to develop greenways between parks or public-private collaborations, would likely result in more stormwater capture, more public support for GI, and greater economic value. Additional modeling efforts that explore more out-of-the-box GI designs and policies could go a long way to convince NYC, and other municipalities, that the benefits of urban greening can only be maximized through a multifunctional, holistic approach. Unfortunately, such models could not be explored in this research and must be relegated to future work with this ABM.

5. Conclusions

NYC plans to spend $1.4 billion to capture the first 2.5 cm of rainfall from 10% of impervious surfaces in combined sewer areas by 2030 (NYC DEP, 2010). Given the financial constraints, physical challenges, and institutional limitations in place, this is a difficult goal to reach. The results of this research emphasize that point. Though the actual greening rates expected in the Bronx, and from NYC's GI program generally, will depend upon many factors not included in this modeling effort—such as soil permeability, bedrock conditions, structural integrity, and utility conflicts—model results are useful for analyzing trends and comparing various approaches to greening. The 10% goal was not achieved in the Bronx under either of the public GI policy scenarios tested here (Model 1 or Model 2). To achieve the 10% goal in the Bronx, the GI program will likely need to be enhanced and expanded, either to allow for other more innovative designs or to encourage GI investments on private property, a goal NYC has already begun to undertake (Local Laws 92 and 94 of 2019). However, the results of Model 2 suggest that a more strategic approach to GI siting—one that explicitly considers the perceived public value of GI beyond stormwater management—may help the city get more value from its existing program. Integrating GI with other initiatives, such as the sustainability goals outlined in OneNYC (NYC, 2015), could have synergistic results, with improved stormwater capture rates and more co-benefits available for New Yorkers.

This paper explored only one alternative to NYC's existing GI program. Since the results hint that a more multifunctional approach to GI can offer enhanced benefits, the next step is to examine what some of those scenarios might look like. Other models to consider include using GI to address air quality concerns or vulnerability to coastal storms (NYC 2015) and testing out various strategies to encourage greening on private property (Gundlach, 2017). Although outside the scope of this work, future efforts could also include a sensitivity analysis of the different models to determine which parameters, constraints, and rules have the greatest impact on stormwater capture and the other co-benefits associated with GI; such work could provide insights into which aspects of the NYC GI program are the most critical to creating a successful GI policy.

Data Availability Statement

All data used to define the spatial bounds of this research (e.g., sewersheds and census blocks) are publicly available through the NYC Open Data Portal (NYC 2017). All other data used in this research are cited in line in the text.

Acknowledgments

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