A Dynamic Life Cycle Assessment of Green Infrastructures

1. Introduction

Green infrastructures (GIs) are nature-mimicking urban stormwater management systems designed to treat, transport, filter, and infiltrate runoff (UNHSC, 2012; USEPA, 2016). In the past few decades, GIs have been increasingly implemented for managing/reducing combined sewer overflow (Jayasooriya and Ng, 2014; Sundberg et al., 2004; USEPA, 2016) and control of nutrients and carbon (Casal-Campos et al., 2015; Gobel et al., 2007; Houle et al., 2013; Moore and Hunt, 2013; Nowak and Crane, 2002; Tzoulas et al., 2007). They have also been widely recognized for their functions in terms of flood/drought mitigation, and heat island effect reduction (Lovell and Taylor, 2013; Zahmatkesh et al., 2014). These benefits have been acknowledged by the US Environmental Protection Agency (EPA) by the addition of their use as a "maximum extent practicable" option under the municipal separate storm sewer systems (MS4) final ruling in 2016 (USEPA, 2017).

Stormwater management prior to the implementations of GIs was primarily focused on peak runoff reductions (USEPA, 2016). However, rulings under the 1990 National Pollution Discharge Elimination System (NPDES) require stormwater to be managed for pollution reduction and water quality improvement, mandating reduction of pollutants such as toxic organics, heavy metals (e.g., zinc, lead, chromium), and nutrients (USEPA, 2016). While these mandates create opportunities for co-optimizing the quantity and quality of stormwater, recommendations of the NPDES are on a sole basis of a system's use phase assuming steady state. However, the impacts associated with GIs' construction and maintenance as well as the dynamic changes of system performance are ignored, which can potentially result in sub-optimization or a shift of environmental burdens between different life cycle stages.

A life cycle perspective is hence imperative to achieve the holistic design, implementation, and management of GIs. Life cycle assessment (LCA) has been increasingly used to evaluate the cradle-to-grave impacts and benefits associated with GIs (Andrew and Vesely, 2008; Brudler et al., 2016; Byrne et al., 2017; Casal-Campos et al., 2015; De Sousa et al., 2012; Flynn and Traver, 2013; Hengen et al., 2016; Jeong et al., 2016; Jones and Hunt, 2010; Kirk, 2006; Kosareo and Ries, 2007; Moore and Hunt, 2012; O'Sullivan et al., 2015; Saiz et al., 2006; Spatari et al., 2011; Vineyard et al., 2015; Wang et al., 2013; Xu et al., 2017). These LCAs are primarily focused on characterizing the material and energy flows within individual applications of GIs (Flynn and Traver, 2013; Jones and Hunt, 2010; Moore and Hunt, 2012; Spatari et al., 2011; Wang et al., 2013), comparing GIs with conventional systems (Brudler et al., 2016; Byrne et al., 2017; De Sousa et al., 2012; Kosareo and Ries, 2007; Saiz et al., 2006; Vineyard et al., 2015), evaluating the integration of GIs into the existing grey infrastructure systems (Casal-Campos et al., 2015; Jeong et al., 2016; Wang et al., 2013), or comparing multiple types of GIs in a particular application (Andrew and Vesely, 2008; Hengen et al., 2016; Kirk, 2006; Xu et al., 2017). However, only seven of these studies included the water treatment benefits provided by the GIs during the use phase (Brudler et al., 2016; Byrne et al., 2017; Flynn and Traver, 2013; Kirk, 2006; Kosareo and Ries, 2007; Wang et al., 2013; Xu et al., 2017). Out of the seven studies, four utilized averaged field measurements taken from the actual GI applications (Brudler et al., 2016; Flynn and Traver, 2013; Kirk, 2006; Xu et al., 2017), while the other three applied averaged removal efficiencies taken from the literature (Brudler et al., 2016; Byrne et al., 2017; Kosareo and Ries, 2007; Spatari et al., 2011; Vineyard et al., 2015; Wang et al., 2013; Wang et al., 2014). The use of static treatment data significantly limits the transferability of these previous studies to different geographical locations, pollutant loadings, or treatment capacities; and hence the generalizability of the findings from the previous studies.

In fact, little consensus has been reached through previous GI LCAs. For example, bioretention systems have been studied in areas such as the northeast (Kirk, 2006; Wang and Zimmerman, 2015) and southeast (Jeong et al., 2016) US as well as in China (Xu et al., 2017). The reported impacts vary significantly, ranging from 1.0-20200.0 kg CO_2 eq. in greenhouse gas (GHG) emissions, -176.0 to -0.1 kg N eq. in nitrogen emissions/reductions, and -7.6 to -0.6 kg P eq. in phosphorous emissions/reductions for systems sized for treating 2.54 cm (1 inch) of precipitation falling on 4047 m^2 (1 acre) of catchment area (Houle et al., 2013; Kirk, 2006; Wang et al., 2013; Xu et al., 2017). This inconsistency further demonstrates the importance of considering heterogeneous geospatial and temporal characteristics (e.g., varied rainfall patterns, pollutant fluxes, and local land/construction costs) as well as each system's individual characteristics (e.g., size, life span, and treatment efficiencies) in GI LCAs. Spatial changes in land use or impervious coverage can cause drastic changes in pollutant loads and runoff volumes, each affecting the overall removal efficiency of GIs (USEPA, 2016). Temporal variations such as seasonal or climate change (USBR, 2013) can affect the GIs' performance through changes in biological activities as well as in rainfall depths and patterns (UNHSC, 2012). An enhanced understanding of how GIs respond to such spatial and temporal changes could help guide and support future design and implementation of GIs. Nevertheless, to our knowledge, none of the previous GI LCAs have the ability to predict the performances of multiple types of GIs based upon dynamic environmental and system characteristics considering both the quantity and quality of stormwater.

The goal of the current study is to develop a dynamic LCA framework which can be generalized to different environmental and system conditions to inform the future design and optimization of GI applications. We use system dynamics models to capture the dynamic pollutant retention/removal during the use phase of seven different types of GIs. Use phase is the focus of the dynamic simulation given the expected climate and pollutant loading fluctuations over the life span of the GIs. The system dynamics models are then integrated into a LCA framework to perform a dynamic assessment of the GIs' performance under different geographical locations, land uses, system sizes, and climate change scenarios. In this study, we demonstrate the modeling framework via focusing on the life cycle nutrient removal/emissions of the GIs. Nevertheless, the modeling framework can be extended to other types of contaminants when sufficient field data become available.

2. Methodology

2.1. System Overview

The seven types of GIs investigated in this work are: vegetated swale, wet pond, sand filter, subsurface gravel wetland, bioretention system, permeable pavement, and tree filter. A baseline life cycle assessment and systems dynamics model was developed and calibrated for each GI based upon the systems that are currently installed on the campus of the University of New Hampshire (UNH; Durham, NH). These GIs are installed close to each other within the same catchment area. Durham, NH has a humid continental climate with cold and snowy winters and warm summers (UNHSC, 2012). Average monthly temperatures vary from -5ºC in January to 21 ºC in July (USNCDC, 2017). Monthly precipitation (rainfall plus snowmelt) is the lowest in January (8.9 cm) and the highest in November (11.8 cm) (USNCDC, 2017).

All GIs were sized to treat the runoff from 2.54 cm (1 inch) of precipitation falling on 4,047 m^2 (1 acre) of catchment area, which is defined as a functional unit (FU) for this study. GIs that were not originally designed for 4,047 m^2 of catchment area (vegetated swale, permeable pavement, and tree filter) were scaled to 1 FU for comparison purposes. Particularly, the material and energy consumptions for constructing and maintaining the three GIs were scaled linearly. The economic costs of the three GIs were scaled using the six-tenth rule (Wittholz et al., 2008) (Section-6 of the supporting information). These systems were constructed in 2004 and stormwater runoff and treatment data were recorded up through 2010. The water quality parameters investigated are dissolved inorganic nitrogen (DIN) and total phosphorus (TP). DIN is removed primarily through the denitrification processes facilitated by microbes (Follett, 1995), while TP is removed primarily via physical removal (solids) and adsorption to sediments (dissolved forms). A notable difference between summer and winter treatment capabilities was observed which is due primarily to changes in biological activities and soil permeability. Table 1 summarizes the GI system footprint and median annual, summer, and winter removal efficiencies for each GI.

Table 1: Design footprint based upon one functional unit and median seasonal/annual removal efficiencies of the seven investigated green infrastructures *(UNHSC, 2012)*

Green Infrastructure Systems	System Footprint (m^2)	Median Annual Removal (%)		Median Summer* Removals (%)		Median Winter** Removals (%)	
		DIN	TP	DIN	TP	DIN	TP
Vegetated Swale	130	0.0	0.0	0.0	0.0	0.0	0.0
Wet Pond	300	32.7	0.0	63.6	0.0	9.8	0.0
Sand Filter	221	0.0	33.4	0.0	30.9	0.0	34.9
Subsurface Gravel Wetlands	507	75.0	57.6	84.5	57.6	33.3	57.6
Bioretention System	25	32.3	12.0	44.0	12.1	19.6	0.0
Permeable Pavement	3872	0.0	57.5	0.0	0.0	0.0	70.3
Tree Filter	26	1.4	0.0	7.6	0.0	0.0	0.0

* Summer spans the months of May through October.
** Winter spans the months of November through April.

2.2. Life Cycle Environmental and Economic Assessment

A life cycle environmental and economic assessment was first carried out to investigate the environmental and economic tradeoffs of the seven GIs located in Durham, NH over their assumed life span of 30 years (Houle et al., 2013; Jeong et al., 2016; O'Sullivan et al., 2015; Wright et al., 2016). Inventories for these GIs were created over the following life cycle phases: raw material extraction, processing, transportation, construction, use, and maintenance. End-of-life phase is not considered within this study as its impacts haven been considered to be insignificant (Jeong et al., 2016). Material and energy requirements during the construction and maintenance stages were modeled after construction blueprints of the GIs and supplemented by literature data (Houle et al., 2013; Kirk, 2006; UNHSC, 2012; UNHSC, 2016). The primary maintenance activities include system inspections, removal of accumulated debris, and trimming/removal of aboveground vegetation. Detailed life cycle inventories are provided in Section S-1 of the supporting information (SI). Removal and retention of nutrients during the use phase was simulated via a system dynamics model (SDM) on a daily time step (described in Section 2.3). SimaPro 8.3 and the Ecoinvent 3 database were used for life cycle impact assessment. Four types of environmental impacts were investigated: cumulative energy demand (Cumulative Energy Demand V1.09 method), carbon footprint (IPCC 2013 100a V1.02 method), and freshwater and marine eutrophication potentials (ReCiPe Midpoint Hierarchist V 1.12 method). These impact categories were chosen based upon their prevalence among previous GI LCAs (Byrne et al., 2017; Casal-Campos et al., 2015; Flynn and Traver, 2013; Kirk, 2006; Lundin and Morrison, 2002; Wang et al., 2013).

We investigated the impacts associated with retrofitting the existing landscape with GIs, which is a common practice in real world applications (NYDEC, 2015; UNHSC, 2007). Wet ponds, sand filters, subsurface gravel wetlands, and bioretention systems have replaced existing greenery. Permeable pavement has replaced existing pavement surfaces. Lastly, tree filters have replaced existing concrete sidewalk surfaces. Hence, carbon sequestration is negligible for all systems except for tree filters, assuming these trees were never cut.

Life cycle cost data for the construction and maintenance phases of the GIs were directly sourced from (Houle et al., 2013; UNHSC, 2012; UNHSC, 2016) (Section S-1 of the SI). They were then converted to net present values in 2017 US dollar with an assumed discount rate of 5% (Wang and Zimmerman, 2015). The economic benefits related to the reduction of peak flows and nutrients were not considered in this study.

2.3. Integrating Dynamic Modeling of Nutrient Removal with the LCA

An SDM was developed to simulate the daily nutrient (nitrogen and phosphorous) retention and/or removal within the GIs in response to climate, pollutant loading, and system design variations over 30 years. Vensim DSS® was used, which utilizes stocks (e.g., nutrients accumulation in GIs) and its associated inflows (e.g., nutrient deposition) and outflows (e.g., nutrient removal) to dynamically characterize GIs' performances. The SDM developed in this study consists of two major segments. The first simulates the nutrient accumulation in the catchment area, whereas the second simulates the nutrient retention and/or removal within the GIs (Figure 1). The following sections are intended to provide an overview of the SDM. More details related to the model are provided in Section S-2 of the SI.

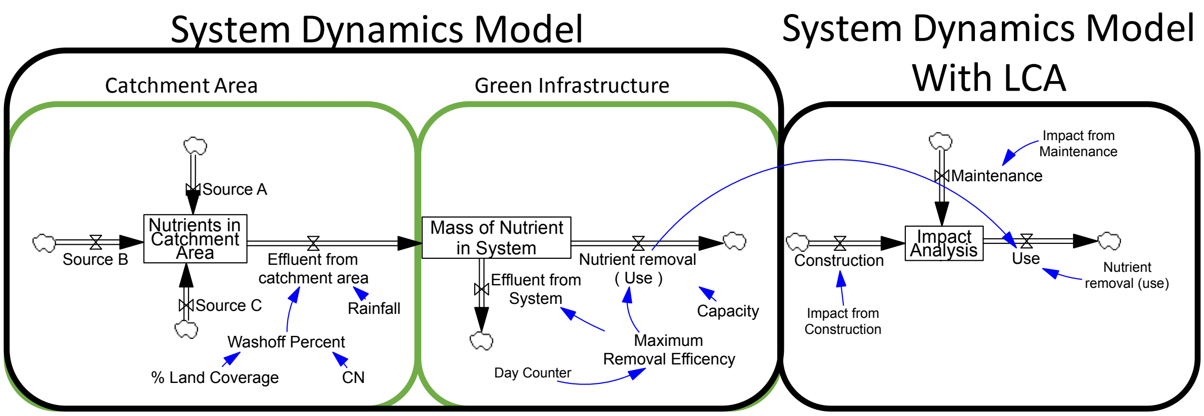

Figure 1: Base green infrastructure system dynamic model showing nutrient flows into and out of the catchment area, green infrastructures, and impact analysis stocks

2.3.1. Catchment Area Model

Nutrient accumulation in the catchment area was calculated as an integral of the daily nitrogen and phosphorus fluxes in and out of the catchment area (Equation 1).

$$N_T = \int_{t_0}^{t} (\sum_i K_{i,t} - E_t)dt + N_{t_0} \qquad \text{(Equation 1)}$$

Where:

N_T = Total accumulation of nutrients in the catchment area, kg;

$K_{i,t}$ = Deposition of nutrients to catchment area from inflow i, kg/day;

E_t = Removal of nutrients from catchment area by runoff, kg/day;

N_{t0} = Initial nutrient mass in the catchment area, 0 kg; and,

t = time, days.

Four nitrogen inflows into the catchment area are simulated: atmospheric deposition, farmland fertilization, lawn maintenance, and automobile exhaust (Miller, 2005; Trowbridge et al., 2014). Atmospheric deposition rate of nitrogen was assumed to be 1.26 kg/ km^2-day evenly distributed within the catchment area (Miller, 2005). Nitrogen application on farmlands was assumed to be 5,336 kg/km^2-week, which was calculated based upon the total mass of nitrogen from fertilizers and manures applied across US farms in 2007 (USEPA, 2007; USEPA, 2011) and the total area of farmlands in the US (USDA, 2007). A weekly fertilization frequency during the months in which the average temperature is equal to or larger than 10 ºC was assumed (UNHSC, 2012). Lawn maintenance activities include fertilizing and grass clipping (Boschma et al., 2017), which are assumed to occur at the same time as farm fertilization and with the same fertilization rate. The nitrogen deposition rate from grass clippings was assumed to be 9,748 kg/km^2 (W.M. Colt, 2008). Nitrogen deposition from parking lots and driveways was calculated based upon the average daily nitrogen deposition from automobiles to a parking lot reported by the EPA, 0.149 kg/km^2, and adjusted to account for seasonal traffic fluctuations (USEPA, 1999).

Three phosphorus inflows into the catchment area were modeled: farmland fertilization, lawn maintenance, and foliage deposition. Phosphorous application rate onto farmland was assumed to be 1,689 kg/km^2-week with the same application frequency as nitrogen (USDA, 2007; USEPA, 2007; USEPA, 2011). Phosphorous flow simulated for lawn maintenance only includes grass clippings as phosphorous in lawn fertilization is prohibited in New Hampshire (Hagen, 2014). The amount of phosphorous released during each mowing event was assumed to be 34.9 kg/km^2-week (Soldat and Petrovic, 2008). Arboreal phosphorous deposition rate in the tree covered catchment area was assumed to be 1.06 kg/km^2-day (Gosz et al., 1972).

Nutrient outflow from the catchment area was modeled using the weighted curve number method (USDA, 1986) combined with a model developed by Deng et al. (2005) which predicts the percentage of pollutants being washed off based upon surface runoff (Deng et al., 2005).

Curve numbers for different land types were obtained from the United States Department of Agriculture (USDA, 1986) (Table 3). Land use of the Durham catchment area was approximated via aerial imaging (Google, 2018). A weighted curve number for the catchment area was calculated based upon the percentage of each land type. Daily precipitation data (both rainfall and snowmelt) were sourced from the National Oceanic and Atmospheric Administration through the climate station closest to the study site with the most complete data (USNCDC, 2017). Additional details of the nutrient outflow calculations are provided in S-2 of the SI.

2.3.2. GI Model

Nutrient accumulations within the GIs were calculated as an integral of daily nutrient inflow (e.g., nutrient loading from the catchment area runoff) and outflows (e.g., biological nutrient removal or nutrient leaving GI without treatment) (Equation 2).

$$N_R = \int_{t_0}^{t} (E_t - \sum_j O_{j,t})dt + N_{R_{t_0}} \qquad \text{(Equation 2)}$$

Where:

N_R = Nutrients within the GI, kg;

E_t = Nutrient inflow into the GI at time t from the catchment area, kg/day;

$O_{j,t}$ = Nutrient outflow j at time t from the GI, kg/day;

N_{Rt0} = Initial nutrient mass in the GI, 0 kg; and

t = Time, days.

Nutrient removal by the GIs depends on two parameters: the nutrient holding capacity and the nutrient removal efficiency. The nutrient holding capacity serves as an upper limit of the nutrient mass that can be retained by the GIs at a time. When nutrient inflow exceeds the GI's available holding capacity at a precipitation event, the excess nutrient mass overflows without treatment. The nutrient removal efficiency determines the amount of the retained nitrogen that can be removed by microbe activities and/or vegetation uptakes. This only applies to nitrogen as phosphorous is assumed to be removed via adsorption alone and the GIs serve as permanent phosphorous sinks. Instead, a sorption efficiency was applied to represent the percentage of retained phosphorous that is effectively adsorbed and removed from the environment. Nutrient masses beyond the removal/sorption efficiency was assumed to be released into the environment. The removal/sorption efficiencies follow the seasonal patterns as outlined in Table 2. The amount of time needed for a certain nitrogen mass to be completely removed (>95% removal) was assumed to be two days (McLaren, 1976), while the phosphorous adsorption was assumed to be instantaneous. The phosphorous adsorption capacities of the GIs were assumed to be not exceeded over the 30-year life span (Xu et al., 2006).

The removal/sorption efficiencies and the holding capacities of the GIs were calibrated for the base models (UNHSC, 2012) following a procedure outlined in S-4. The calibration start point for the nutrient holding capacities of all GIs was set as the average nutrient mass flowing from the catchment area (0.6 kg of N and 0.1 kg of P) (Houle et al., 2013). The nutrient removal efficiency was first varied to match the simulated and reported annual median removal efficiency for each GI. The nutrient removal/sorption efficiencies should not exceed one or be lower than the reported annual median removal efficiencies. If no match was found within the range, the capacity of the GI was adjusted to re-run the simulation, otherwise, the calibration process stops. Additional information on calibration can be found in the SI.

2.4. Model Validity and Sensitivity Analysis

The modeled nitrogen and phosphorous effluent from the catchment area was evaluated against the reported effluent from both the Durham site and a nearby site (Greenland, NH) with similar characteristics in terms of geography, use, and size (Houle and Ballestero, 2018). Due to the abnormal events such as horse stabling, the Durham site experienced on average higher nutrient mass fluxes and thus was set as the upper bound of the range. Alternatively, the Greenland site was set as the lower bound. The modeled catchment area nutrient effluent values were 0.202 kg N eq. and 0.007 kg P per average inch of rainfall. These values are within the range of the measured values from the two sites 0.04-0.6 kg N eq. and 0.002-0.1 kg P eq per average inch of rainfall (Houle and Ballestero, 2018; Houle et al., 2013; UNHSC, 2016; UNHSC, 2017).

A sensitivity analysis was conducted for the Durham base model to test the influence of system changes on the key model outcomes. The system variables tested include the nitrogen deposition rate on parking lots, the nutrient emission rates from grass clipping and fertilization, and the foliage deposition rate. These variables were selected because they were not calibrated or directly observed from the study site. These values were changed by ±5, 10, 20, 50, 100% and the resulting influence of these changed on the model outputs were documented.

3. Results and Discussions

3.1. Economic and Environmental Performances of GIs

A comparison of the life cycle environmental and economic impacts of the seven GIs reveals important tradeoffs among the different types of impacts as well as the life cycle stages in which these impacts are introduced (Figure 2). Many of the GIs present capabilities of nutrient removal during the use phase but contribute to nutrient emissions during the construction and maintenance phases. Over a 30-year life span, the amount of nitrogen removed by subsurface gravel wetland, wet pond, and bioretention system significantly outweigh their nitrogen emissions, with a net removal of 103.9, 57.2, and 47.8 kg N eq. respectively. This is primarily due to their relatively light construction and maintenance needs and their relatively high biological nitrogen removal capabilities. Although the tree filter has a moderate nitrogen removal capability, the net removal is insignificant due to the high nitrogen emissions from pavement cutting and removal during the construction phase, which highlights the importance of reducing construction impacts in a retrofitting setting.

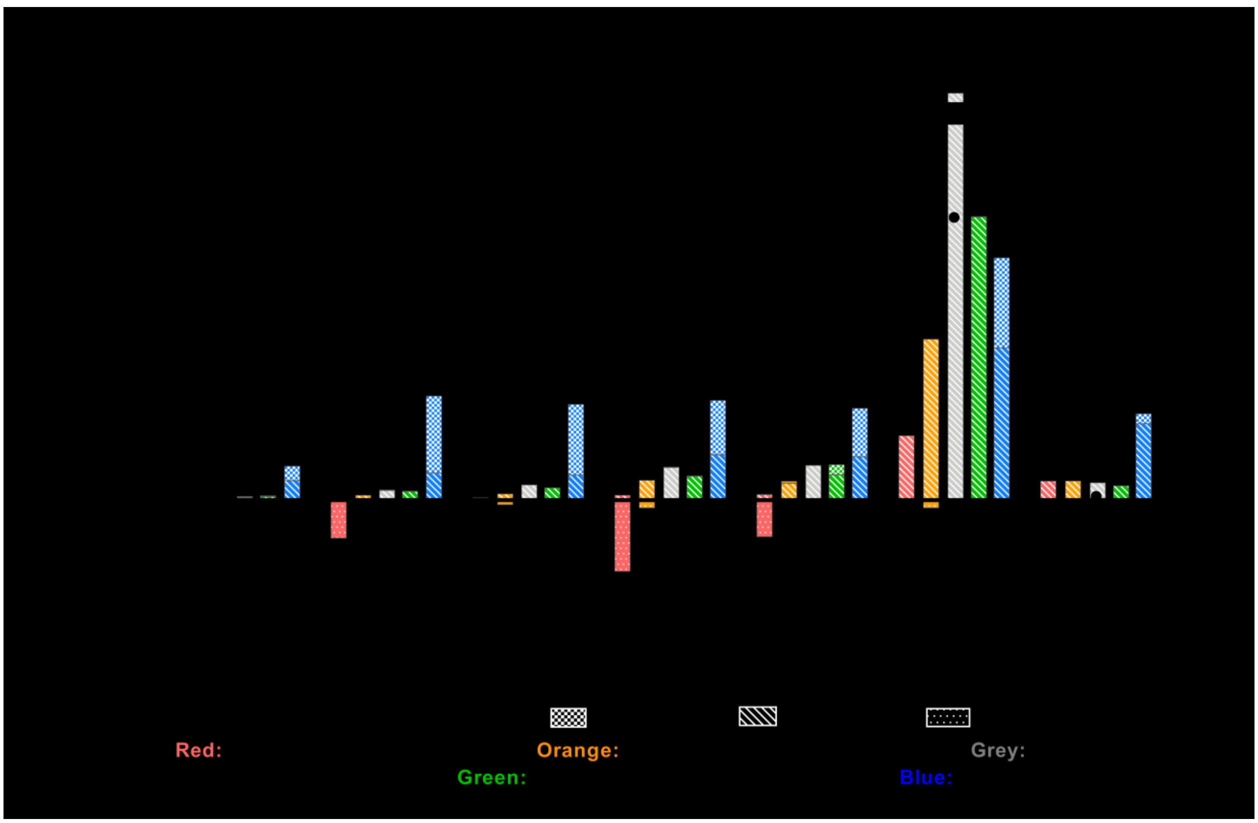

Figure 2:Environmental and economic life cycle assessment by green infrastructure (GI): marine eutrophication (red), freshwater eutrophication (orange), cumulative energy demand (grey), global warming potential (green), and economic cost reported in $2017 (blue) These values are cumulative across the GIs'30-year life cycle. Positive values indicate emissions or costs whereas negative values indicate reductions or cost savings.

Unlike the nitrogen model, none of the systems experience net life cycle reductions of phosphorous. This is because of the low flux of phosphorus from the catchment area which rarely maxes out the systems' treatment capability and allows for the impacts incurred during the construction and maintenance phases to dominate the life cycle. The GI that has the lowest life cycle emission of phosphorus is the sand filter (0.14 kg P eq). Interestingly, the system with the second lowest net emission is the swale which does not perform any treatment across its life cycle. This indicates the importance of understanding and balancing the need of treatment and the emissions from the treatment systems.

Cumulative energy demand (CED) and greenhouse gas (GHG) emissions are primarily influenced by the construction phase of the GIs. Systems that present the highest CED are permeable pavement, which is mainly resulted from transportation of bulk materials such as sand and gravel as well as the production of asphalt. This is followed by bioretention system, subsurface gravel wetland, tree filter, and sand filter. Swale requires the smallest amount of energy due to its simplistic trench design. GHG emissions follow the same order. A comparison of the four types of environmental impacts show that the subsurface gravel wetland stands out as a superior option with the highest net reductions of both nitrogen and phosphorous, while having relatively low energy consumption and GHG emissions. However, tradeoffs exist in the rest of the GIs, as they are either only capable of removing one type of nutrients or require a significant amount of energy for nutrient removals.

In terms of life cycle cost, permeable pavement requires the highest economic inputs of \$379,000 when its catchment area is scaled to 4,047 m^2. This is mainly due to the high construction cost given the system size and the large amount of materials needed. However, it should be noted that these costs are likely to be significantly reduced when the GIs are constructed in conjunction with new construction or renovation of roadways or parking lots. For the rest of the GIs, the wet pond, subsurface gravel wetland, sand filter, bioretention system, and tree filter present similar life cycle costs, ranging from $135,000 to $163,000. Swale has the lowest life cycle cost of $58,000. The majority of these GIs' economic costs occur during the maintenance phase, which indicates alternative maintenance practices or frequencies may be needed to reduce overall cost. A comparison of the GIs' environmental and economic impacts shows that the subsurface gravel wetland is a relatively good option to achieve significant nutrient treatment benefit with relatively low economic cost ($1,405/kg of N eq. and $120,757/kg of P eq.). Although permeable pavement present high construction and maintenance costs, it does not require additional land, and hence could be appealing for cities with land restraints. This is also true with tree filters. These results also show that the peak flow reduction capacity is a limited indicator of the GI's water quality, energy, and economic performances. Hence, it is important to comprehensively understand and assess each system's capabilities in achieving local needs before implementation.

3.2. Scenario Analysis

3.2.1. Geospatial Location Scenarios

The base model was applied to seven additional cities (Table 2) to assess the influence of location on GIs' life cycle nutrient treatment performances. Ten years of precipitation data (2007- 2017) from each city were retrieved and replicated to create a 30-year data set. Inputs that have a seasonal variation were adjusted for each city (USNCDC, 2017).

Table 2: Eight cities and their base climate information used to simulate the removal efficiencies of the green infrastructures under different weather patterns

City (abbr.)	NOAA Region	Annual Precip. (cm)	Avg. Temp. (°C)	Summer Months
Durham, NH (DH)	North Atlantic	228.6	7.2	April-September
Atlanta, GA (AT)	South and Caribbean Region	127.0	17.2	All year
Chicago, IL (CH)	Great Lakes	99.0	10.6	March-October
Dallas, TX (DS)	Gulf of Mexico	104.1	17.8	All year
Phoenix, AZ (PO)	Western	20.3	23.9	All Year
San Diego, CA (SD)	Western	25.4	17.8	All Year
Honolulu, HI (HI)	Pacific Islands	43.2	25.6	All Year
Wichita, KS (WI)	Central	86.4	13.9	February-November

*Summer months are defined as months that have an average temperature of 10ºC or above.

We found the net nitrogen and phosphorous benefits of the GIs have different sensitivity to geospatial changes (Figure 3). Subsurface gravel wetland has the highest life cycle nitrogen removal regardless of geographic locations, followed by wet pond and bioretention system. However, performance of the three types of GIs can vary by 38%, 39%, and 53%, respectively when comparing the best performing city (Atlanta, GA) with the worst (Durham, NH). GIs across all cities experience a net emission of phosphorous. Similar to the nitrogen model, there is a clear ranking in systems across all cities with permeable pavements having the highest net phosphorous emission, followed by bioretention systems, subsurface gravel wetlands, tree filters, wet ponds, and swales. Out of these GIs, permeable pavement and bioretention systems have the highest performance variabilities across different cities.

The performance variabilities across the cities are a combined effect of the seasonal temperature and precipitation patterns within each city, length of growth season (the amount of fertilizer applied), and the GIs’ sensitivity to seasonal temperature changes. We found GIs with larger spatial variabilities generally have larger performance discrepancies during summer and winter months, and hence are more sensitive to changes in the duration of warmer summer months. Furthermore, GIs in wetter areas (e.g., Atlanta and Dallas) generally experience more nutrient removals than arid areas such as Phoenix. Arid areas generally have less frequent rain events, which allows for larger amounts of nutrients to accumulate within the catchment area and is more likely to overload the GIs' capacity when precipitation happens. Such performance fluctuations are important to be considered when adapting existing or new GI systems to different geographical locations.

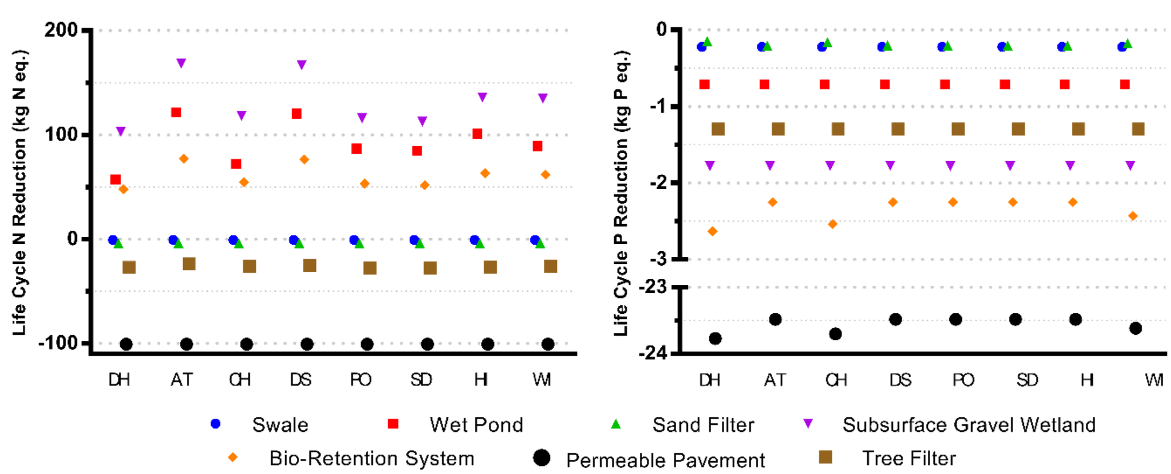

Figure 3: Life cycle nitrogen and phosphorous reductions of the green infrastructures in eight different US cities. Positive values indicate net life cycle reductions; negative values indicate net life cycle emissions.

3.2.2. Land Use Scenarios

Four typical land use types (namely rural, industrial, agricultural, and urban) beyond the base model were studied to quantify their effect on GIs' performance (Table 3) (Rose et al., 2003). As the land use is further diversified, a significant change is observed in terms of the life cycle nitrogen and phosphorous removals (Figure 4). This variation is primarily caused by the changes in the amount and pattern of nutrient loadings in the catchment area. Overall, agricultural land use has the highest life cycle nutrient loadings and removals followed by rural, industrial, and urban land uses, while the base model comes to the last.

Table 3: Land type distribution for four different land uses and the associated curve numbers applied to the studied green infrastructures

Land Type	Curve Number (USDA, 1986)	Durham, NH (%)	Rural (Rose et al., 2003) (%)	Industrial (Rose et al., 2003) (%)	Agricultural (Rose et al., 2003) (%)	Urban (Rose et al., 2003) (%)
Trees	43	5	17	10	40	8
Lawn	49	10	32	25	0	19
Farm	85	0	0	0	50	0
Miscellaneous*	98	5	6	25	5	13
Parking/Driveway	98	80	25	25	5	35
Building	98	0	20	15	0	25

*Miscellaneous coverage includes but is not limited to, street lights, man holes, curbs, walk ways.

Subsurface gravel wetland has the highest life cycle nitrogen removal regardless of land use type, followed by wet pond and bioretention system. However, the differences among the GIs' performances become more prominent as nutrient loadings increase. The prevailing systems in the phosphorous model is generally subsurface gravel wetland followed by sand filter and bioretention system. Unlike the base model, all these GIs are able to achieve net phosphorus removal under the four additional land use types. Performance of permeable pavement has a large fluctuation, and it becomes the second highest phosphorous removing GI in the agricultural land use. This results from the combined effect of the large phosphorous influx and the large phosphorous absorbing capacity and efficiency of the permeable pavement. Collectively, our finding shows that an important nutrient loading threshold exists for the GIs to achieve net positive performance, and it is important to identify and assess such thresholds to inform planning and decision-making.

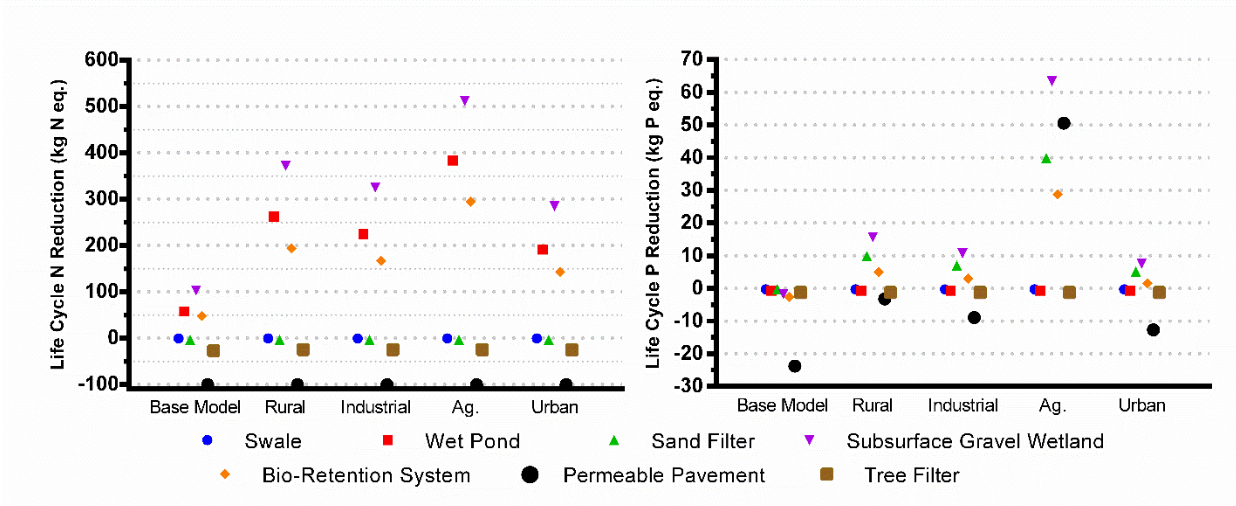

Figure 4: Life cycle nitrogen and phosphorous reductions of the green infrastructures under four land uses. Positive values indicate net life cycle reductions; negative values indicate net life cycle emissions.

3.2.3. System Size Scenarios

Many cities mandate that GIs be designed to treat the water quality volume, which is the runoff from the 2.54 cm (1 inch), 24-hour rainfall event (USEPA, 2010). This often requires the GIs to be designed with a larger footprint to accommodate a static volume of water, and hence can be difficult for more urban based communities to adopt (UNHSC, 2012). We assessed the GIs' performance at 25%, 50%, 75% of the baseline size (NYSDEC, 2015). Annual median removal efficiencies under each size were retrieved from the New Hampshire small MS4 general permit system performance curves (Section S-3 of the SI), which were then used to recalibrate the nutrient loading capacities and removal/sorption efficiencies of the GIs using a similar process as illustrated in Section 2.3.2.

The design size of the GIs has an impact on both its nutrient reduction capacity and its pollution emissions due to the change of materials needed during the construction and maintenance phases, indicating an opportunity for optimization (Figure 5). Indeed, the highest nitrogen reduction was achieved by 75% fully sized subsurface gravel wetland and bioretention systems rather than their fully sized systems. However, the fully sized wet pond system still has the highest performance. This is due to the wet pond's rapid drop in removal efficiency with decreasing system sizes (Section S-3 in the SI).

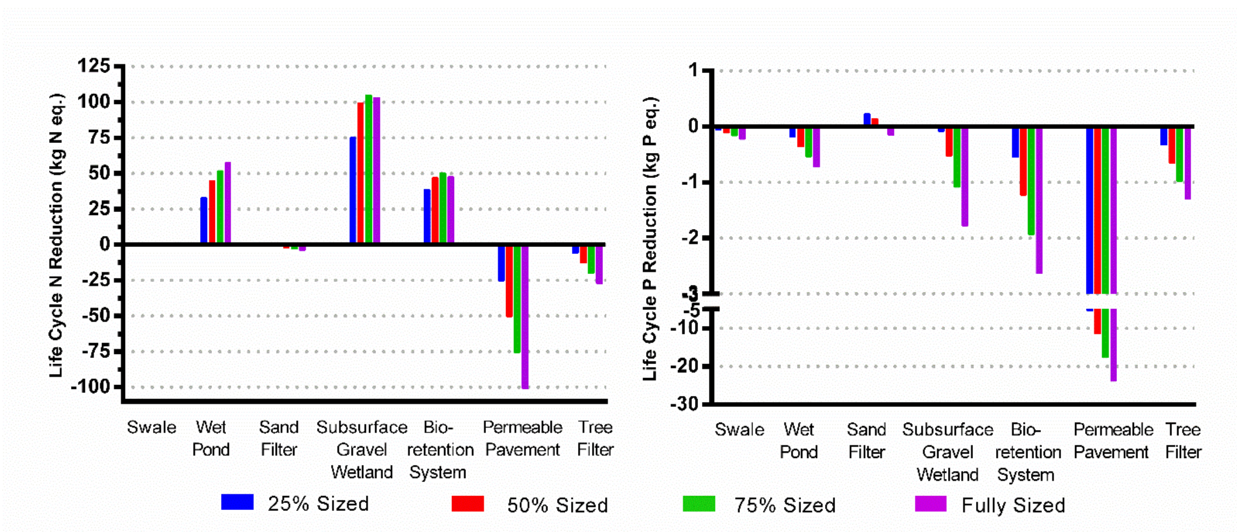

Figure 5: Life cycle nitrogen and phosphorous reductions of the green infrastructures under four design sizes. Positive values indicate net life cycle reductions; negative values indicate net life cycle emissions.

Within the phosphorous results, all systems perform the worst under the fully sized scenario due to the high construction and maintenance impacts and the limited phosphorous treatment need in the base model. However, if placed under the agricultural land use as described in Section 3.2.2, all GIs with phosphorous treatment capabilities will experience the highest net reductions under the 100% fully sized scenario (Section S-7 of the SI). When these GIs are placed under industrial or urban land uses, however, the 75% fully sized scenario becomes the best option in terms of life cycle phosphorous removal. This indicates factors such as local nutrient loadings and GIs' treatment capabilities need to be considered when sizing and planning for GI implementations.

3.2.4. Climate Change Scenarios

Downscaled CIMP5 RCP8.5 (high emission) and RCP2.6 (low emission) models were used to investigate GIs' performances under climate change. The daily average rainfalls were calculated based upon 36 models for the RCP2.6 scenario and 41 models for the RCP8.5 scenario. When the rainfall value is smaller than 0.25 cm, it was assumed no rain occurs on that day (USDA, 1986). Data were obtained for three 30-year periods in early (2004-2033), mid (2034-2063), and late (2064-2093) century (USBR, 2016), to align with the assumed 30-year life span of the GIs (UNHSC, 2012).

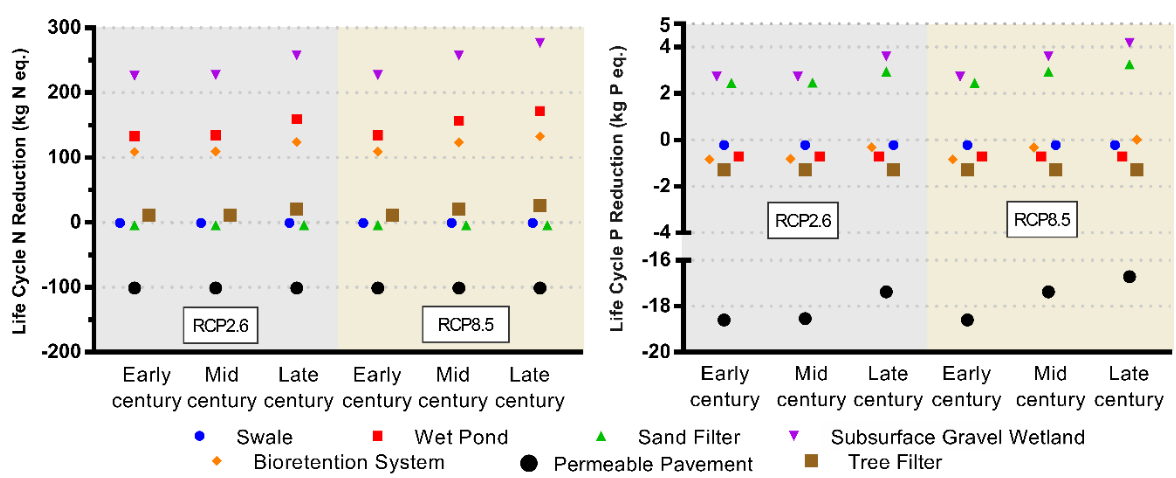

Figure 6: Life cycle nitrogen and phosphorous reductions of the green infrastructures under two climate change scenarios. Positive values indicate net life cycle reductions; negative values indicate net life cycle emissions.

Our results (Figure 6) show nutrient removals by GIs increase over time in the coming century. The RCP8.5 scenario shows a higher nutrient reduction compared with the RCP2.6 scenario as the century progresses. This is because of the more frequent rainfall and longer summer expected under the RCP8.5 scenario, which collectively contributes to less nutrient build-up and a higher overall removal efficiency. Climate change does not change the ranking of the GIs in both nitrogen and phosphorous results. However, certain GIs that do not show nutrient reduction benefits are projected to have a net reduction of nutrients even in the early century (e.g., nitrogen reduction by tree filter and phosphorous reduction by subsurface gravel wetland and sand filter). These dynamic nutrient reduction patterns show the importance of adopting a temporal view when approaching the planning of GIs.

3.3. Sensitivity Analysis

Figure 7 illustrates how changes in the selected input variables affect the life cycle nitrogen and phosphorous removals by the subsurface gravel wetland. Additional figures on sensitivity analysis can be found in Section S-8 of the SI. Within the nitrogen base model, outputs are the most sensitive to significant reductions in nitrogen emissions associated with agricultural fertilization. The nitrogen model is not very sensitive changes in car and atmospheric deposition rates as well as the nitrogen emission rates from grass clipping and lawn fertilization within the studied ranges, as the percentage changes in model outputs are all less than the percentage changes in these input variables. Within the phosphorous model, outputs are the most sensitive to significant reductions in the phosphorous emission rates associated with grass clipping and agricultural fertilization. The phosphorous model is not sensitive to changes in foliage deposition rate.

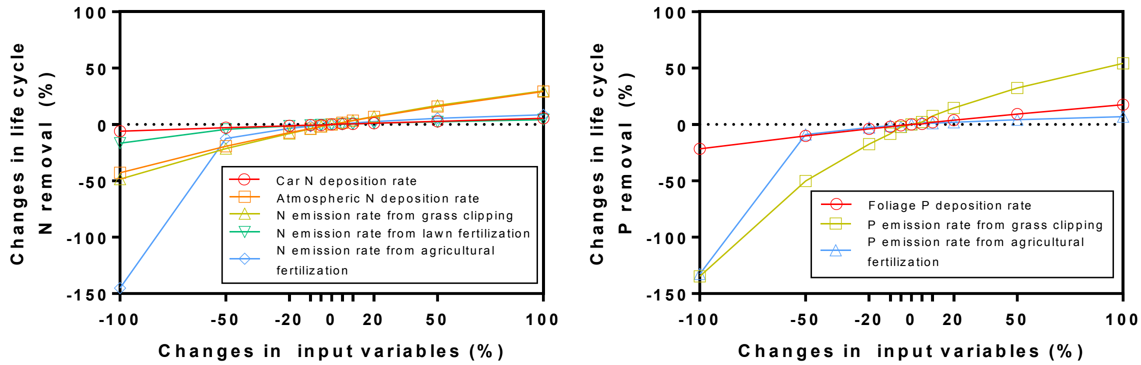

Figure 7: Sensitivity analysis on the impact that changes in input variables have on the life cycle nutrient removals experienced by the subsurface gravel wetland (GW)

4. Policy Implications

Through integrated system dynamics modeling and life cycle assessment, this study provides a comprehensive and generalizable approach in assessing and evaluating different GIs under various spatial and temporal settings. A comparison of GIs' performances under different geospatial location, land use, system size, and climate change scenarios reveal the importance of considering each of these factors in GI planning and decision-making. Seasonal temperature and precipitation patterns influence GIs' microbial activities and the accumulation of nutrients in the catchment area. Meanwhile, local land use patterns influence the pattern and the amount of nutrient loadings. All these factors collectively affect GIs' nutrient treatment efficiencies and their life cycle performances. Our results show an optimal GI size can be estimated when the aforementioned factors are considered. Further, a nutrient loading threshold exists for a certain GI to achieve net positive performances. Such optimal sizes and thresholds are important to be identified to inform the decision-making and future planning of GIs. Based upon our analysis, subsurface gravel wetland is a generally good option with comparatively high nitrogen and phosphorous treatment benefits and comparatively low economic costs, and its ranking remains relatively consistent across the different scenarios examined in this study. Our approach can be generalized to consider additional types of water quality indicators to better inform GI planning and design in the future.

Associated Content

Supporting Information

Sections S-1 – S-8, Tables S1-S19, Figures S1-S15, and text.

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