

High water retention in urban garden soils leads to reduced leachate and elevated evapotranspiration

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Abstract

Among the ecosystem services provided by urban greenspace are the retention and infiltration of stormwater, which decreases urban flooding, and enhanced evapotranspiration, which helps mitigate urban heat island effects. Some types of urban greenspace, such as rain gardens and green roofs, are intentionally designed to enhance these hydrologic functions. Urban gardens, while primarily designed for food production and aesthetic benefits, may have similar hydrologic function, due to high levels of soil organic matter that promote infiltration and water holding capacity. We quantified leachate and soil moisture from experimental urban garden plots receiving various soil amendments (high and low levels of manure and municipal compost, synthetic fertilizer, and no inputs) over three years. Soil moisture varied across treatments, with highest mean levels observed in plots receiving manure compost, and lowest in plots receiving synthetic fertilizer. Soil amendment treatments explained little of the variation in weekly leachate volume, but among treatments, high municipal compost and synthetic fertilizer had lowest leachate volumes, and high and low manure compost had slightly higher mean leachate volumes. We used these data to parameterize a simple mass balance hydrologic model, focusing on high input municipal compost and no compost garden plots, as well as reference turfgrass plots. We ran the model for three growing seasons under ambient precipitation and three elevated precipitation scenarios. Garden plots received 12–16% greater total water inputs compared to turfgrass plots because of irrigation, but leachate totals were 20–30% lower for garden plots across climate scenarios, due to elevated evapotranspiration, which was 50–60% higher in garden plots. Within each climate scenario, difference between garden plots which received high levels of municipal compost and garden plots which received no additional compost were small relative to differences between garden plots and turfgrass. Taken together, these results indicate that garden soil amendments can influence water retention, and the high water retention, infiltration, and evapotranspiration potential of garden soils relative to turfgrass indicates that hydrologic ecosystem services may be an underappreciated benefit of urban gardens.

Introduction

Urban ecosystems are highly engineered environments that are often characterized by extensive impervious surface cover and highly altered hydrology. The built environment and impervious cover of urban ecosystems—roads, sidewalks, and roofs—increase the magnitude and speed of movement of people and goods, and also facilitate transport of water and nutrients, contributing to flooding and water pollution (Miller et al. 2014). Stormwater storage and infiltration is an important feature of urban green infrastructure design to mitigate flooding and reduce nutrient transport to water bodies, especially given increases in extreme precipitation events due to climate changes (Donat et al. 2016; Pathak et al. 2017). Evaporation and transpiration (together, evapotranspiration or ET) are important factors in urban heat island reduction (Donat et al. 2016; Pathak et al. 2017). The extent of lawns and gardens and how these greenspaces are managed interacts with climate and influence urban water demand for irrigation (Flörke et al. 2018).

Greenspaces play important roles in facilitating ecosystem services related to hydrology in urban ecosystems. Turfgrass is characterized by relatively high infiltration and ET, and low runoff rates (Monteiro 2017). Urban trees can decrease runoff through canopy interception, enhance percolation driven by tree roots, and subsequent transpiration (Kuehler et al. 2017; Berland et al. 2017; Rahman et al. 2019). Green stormwater infrastructure such as rain gardens and retention basins are intentionally designed for stormwater retention or infiltration (Karnatz et al. 2019). Green roofs, which are typically constructed in areas with high impervious cover, are designed to decrease runoff through retention and ET (Raimondi and Becciu 2020).

While the hydrologic properties of stormwater green infrastructure, turfgrass, and urban tree canopies have been relatively well-studied, less attention has focused on the hydrologic role of urban vegetable gardens. Urban food cultivation has increased in popularity in recent decades (Fox 2011), with primary goals such as increasing food security and diet diversity, particularly in low income areas (Warren et al. 2015; Opitz et al. 2016); building community; and as a healthy recreational activity to increase connection to food production (McDougall et al. 2019). Although relatively low in spatial extent (between 0.1-3% of land area; Metson and Bennett 2015; Small et al. 2019), urban gardens are highly distributed and may function more similarly to engineered stormwater green infrastructure than to other types of urban greenspace. Urban gardens are characterized by high compost inputs (Small et al. 2019) and porous spoils, potentially resulting in high water storage capacity and ultimately higher ET from crops growing in nutrient-rich garden soil (Qiu et al. 2013). We previously documented seasonal ET rates in garden plots that were nearly twice as high as in reference turfgrass plots, with lower leachate fluxes in garden plots despite additional water inputs from irrigation (Small et al. 2020).

The goal of this study was to quantify the effects of different soil management practices in urban gardens on the physical and biological processes affecting garden hydrology. We first analyzed the results of three years of hydrologic data from experimental garden plots that received different types and amounts of compost and synthetic fertilizer. We then developed a simple mass balance hydrology model, parameterized using data from this study, and used this model to compare the fate of water in gardens or turfgrass across a range of precipitation scenarios. We tested the hypothesis that high compost garden soil is characterized by elevated water storage, decreased leachate, and ultimately higher ET.

Methods

Study area and design

We conducted a multi-year study using the Stewardship Garden at the University of St. Thomas in St. Paul, MN. Established in 2011, the research garden contains 36 raised garden beds measuring 4 m² and 0.3 m deep (Figure S1). At the start of the current study in 2017, soil from previous projects was replaced and homogenized. Each raised bed was divided into four subplots in which the following crops were planted and rotated annually: 1) carrots; 2) bush beans; 3) bell peppers; and 4) cabbage (2017) or collards (2018, 2019). We randomly assigned each of the experimental plots to one of 6 soil amendment

treatments previously described by Shrestha et al. (2020). Briefly, soil treatments consisted of a: 1) control treatment in which no compost or fertilizer was added (nofert); 2) synthetic fertilizer to meet crop N demand and P (synthetic); 3) a higher application rate of manure compost targeted to meet crop N demand (high manure); 4) a lower application rate of manure compost targeted to meet crop P demand, with supplemental N fertilizer to meet crop N demand (low manure); 5) a higher application rate of municipal compost targeted to meet crop N demand (high municipal compost); and 6) a lower application rate of municipal compost targeted to meet crop P demand, along with supplemental N fertilizer to meet crop N demand (low municipal compost). Compost properties and application rates are described in Tables S1 and S2. Mean garden soil organic matter (loss on ignition method) ranged from 8% on the no fertilizer treatment to 12.6% in the high municipal compost treatment (Table S3). For more detailed information about the study area and the experimental design see Small et al. (2018) and Shrestha et al. (2020).

Total water inputs, soil moisture, and other meteorological data

Soil moisture was measured 3-4 times per week at a depth of 5 cm, with three measurements recorded from each garden subplot, between June-August from 2017-2019, using a General DSMM 500 soil moisture meter. We used these direct measurements (data reported as %) for statistical analyses, but we converted values for the mass balance model (described below) in 2017 by collecting 16 40 mL soil cores from each soil amendment treatment and measuring water content as the difference between the initial (wet) mass and the mass after drying for 48 hours at 40°C (Fig. S2). Soil moisture readings are presented as % by volume ($[\text{mL water/mL soil}] \times 100$).

Meteorological data was collected at hourly intervals in the research garden beginning in June 2017. Rainfall was measured using a ECRN-50 rain gauge (Part # 40655, METER); solar radiation was measured using a PAR sensor (Part # 40003, METER); temperature and relative humidity were measured using a VP-4 sensor (Part # 40023, METER); and wind speed was measured using a Davis Cup anemometer (Part #40030, METER). Data was recorded using an Em50 data logger (Part 40800, METER).

Throughout the growing season, soil moisture was maintained at > 15% in our study plots through a combination of rainfall and irrigation. When irrigation was required, we watered evenly over the 4 m² raised beds for a set time (30, 45, or 60 seconds) and estimated the volume of water added by measuring the amount of time it took to fill an 11 L bucket at that flow rate. All garden study plots received equal irrigation inputs. Total water inputs for each weekly interval were calculated as the sum of ambient rainfall and irrigation inputs. Reference turfgrass plots located adjacent to the garden received ambient rainfall but did not receive supplemental irrigation.

Leachate collection

Prior to the beginning of the experiment in 2017, we installed lysimeters in the center of each of the 128 garden subplots, plus five additional turfgrass reference plots. Lysimeter construction, installation, and data collection were previously described in Small et al. (2018) and Shrestha et al. (2020). Briefly, we

constructed lysimeters by attaching plastic funnels with diameter of 11.8 cm to 1 L polyethylene bottles fitted with Tygon tubing for sampling. We buried the lysimeters at a depth of 0.3 m. We collected and recorded leachate volume from the lysimeters weekly throughout the growing season by emptying the collection bottle with a 50 mL syringe.

Statistical analysis

We tested for differences in soil moisture and leachate volume among soil treatments using general linear models. For mean weekly soil moisture, our models included four predictor variables: soil treatment, weekly total water inputs (rainfall and irrigation), crop type, and year. Because the relationship between weekly water inputs and soil moisture was nonlinear above inputs of 5 cm/week, weeks exceeding this total were excluded from the statistical model (a total of 7 out of 41 weeks).

For weekly volume of leachate collected, our models included weekly total water inputs (rainfall and irrigation), crop type, year, and weekly mean soil moisture (on a volume basis). To identify the best fit and most parsimonious models for both weekly soil moisture and weekly volume of leachate collected, we used multimodal inference and the Akaike Information Criterion (AIC) approach to model selection in R. We tested assumptions of normal distribution using the diagnostic plots in R; we used residual vs. fitted plots to test for equal variance and the Q – Q plot to assess normality. We also evaluated variance inflation factors and confirmed they were low (< 3), indicating insignificant collinearity between our variables. Including four predictor variables in our models generated a total of 15 models. To select the best fit model, we evaluated the 15 models from a R^2 , adjusted R^2 , AIC, DAIC, and model weight perspective.

Mass balance hydrology model

We created a simple mass-balance hydrology model to test assumptions about underlying processes by comparing model output with observed data. We modeled soil moisture (SM) as L of water within a 1m x 1m x 0.3m (300 L) experimental garden plot:

$$dSM/dt = \text{precipitation} + \text{supplemental irrigation} - \text{water leachate} - \text{evapotranspiration}$$

Daily precipitation and supplemental irrigation (mm/d, or L/m²/d) were inputs to the model as described above. Water leachate (mm/d, or L/m²/d) was modeled based on the difference between modeled soil moisture and soil water capacity. Water capacity was modeled as a function of soil % organic matter, based on the relationship between the mean %OM for each soil amendment treatment and the maximum observed soil moisture in that treatment ($R^2 = 0.57$). Water storage in excess of water capacity was assumed to be exported as leachate.

We calculated evapotranspiration (mm/d, or L/m²/d) based on the Penman-Monteith equation (Zotarelli et al. 2010), using mean daily solar radiation, maximum and minimum relative humidity, maximum and minimum temperature, and mean wind speed as inputs. The calculated reference evapotranspiration rate

(representing turfgrass) was converted to potential crop evapotranspiration using seasonally varying crop coefficients ranging from 0.55-1.2, with maximum values in the middle of the growing season (based on values reported in Satler 2016). Potential crop evapotranspiration was multiplied by a correction factor, k_s , that is a function of soil moisture (Zotarelli et al. 2010), adjusting ET downward in drier soil. Between soil moisture values of 6% and 21%, k_s increases linearly from 0 to 1. During the parameterization process, we adjusted calculated ET using a correction factor of 2 to achieve a good correspondence between modeled and observed soil moisture and cumulative leachate values.

The simulation was run from 27 May 2017 - 25 October 2019 (881 days), spanning three growing seasons, with $dt = 1$ day. The model was run using Stella Architect (1.5.2) using the Euler integration method. Modeled values for soil moisture and cumulative leachate were compared against observed values for 2017 and 2018 in the garden-municipal compost (high application rate), garden-no compost, and reference turfgrass plots. Model equations and parameter values are found in the appendix.

The model was used to compare cumulative evapotranspiration and leachate from ambient precipitation (Scenario 0) with three alternative climate scenarios. In Scenario 1, we simulated a 30% increase in annual rainfall (Easterling et al. 2017) by multiplying daily observed rainfall totals by 1.3. Scenario 2 simulates elevated rainfall only during the spring and fall (Easterling et al. 2017), achieved by multiplying daily rainfall for Julian days 80-172 and 264-355 by a factor of 1.3. Scenario 3 simulates an increase in magnitude of extreme precipitation events (Hayhoe et al. 2010) achieved by multiplying any daily rainfall total greater than 5.08 cm (2 inches) by a factor of 1.25. Supplemental irrigation was maintained at ambient levels (no irrigation for turfgrass) in these scenarios. For each scenario, we also calculated cumulative leachate and ET fluxes into water derived from precipitation and water derived from irrigation. To do this, we separately modeled stocks of soil water derived from precipitation and soil water derived from irrigation, with inflows being the known daily inputs from each source, and outflows were partitioned by multiplying the calculated total flux of leachate or ET by the relative composition of the total soil water stock.

Results

Total weekly water inputs

The mean total weekly water inputs (the weekly sum of irrigation water + rainfall) were 3.65 (\pm SE, 0.59) cm in the 2017 growing season, 2.67 (\pm 0.66) cm in 2018, and 3.52 (\pm 0.85) cm in 2019. Total seasonal supplemental irrigation inputs mostly occurred during June and July, and totaled 14.9 cm in 2017, 11.0 cm in 2018, 7.03 cm in 2019. In 2017, 12 out of 14 growing season weeks had less than 5 cm of total water inputs, and in 2018 and 2019, total weekly water inputs were generally below 2.5 cm, though every year had at least one week over 7.5 cm (Fig 1.).

Soil moisture

The mean weekly soil moisture across all garden plots for 2017 was 16.7% (± 0.065) (mean (\pm SE)), 14.8% (± 0.082) for 2018, and 16.5% (± 0.070) for 2019. Soil moisture in the reference turfgrass plots (only measured in 2017) was slightly lower, with a mean of 0.247 (± 0.0138) mL H₂O mL⁻¹ soil.

Soil moisture was positively related to weekly water inputs between 0-5 cm/week; soil moisture was not related to water inputs at higher levels than 5 cm/week (Fig. S3, S4). Excluding weeks with high (>5 cm) water inputs, the best-fit model—as determined by R², adjusted R², and through AIC model selection criteria—for soil moisture included weekly total water inputs, soil treatment, crop type, and year (Table 1). This best fit model and its four predictor variables explained 26.4% of the variation within weekly soil moisture and treatment explained 7.6% of that alone (Table 1). Weekly total water inputs (sum of irrigation plus precipitation) was a weak explanatory variable and was weakly correlated with weekly soil moisture (Fig. 1, Table 1). We report the coefficients of the logistical model in Table 2.

Mean observed soil moisture in garden plots varied across years (Table 1), with lowest mean values observed in 2018 and highest values in 2019 (Table 2). Weekly soil moisture varied across treatments (Table 2). The manure compost treatments (both high- and low-input levels) generally had the highest weekly soil moisture, whereas the low municipal compost and synthetic fertilizer treatments had the lowest values (Table 2). We found differences in weekly soil moisture among crop types (Table 1), with highest values observed in subplots growing beans (Table 2).

Leachate volume

Observed leachate volumes across all garden plots averaged 0.51 \pm 0.011 cm in 2017, 0.975 \pm 0.016 cm in 2018, and 1.67 \pm 0.023 cm in 2019. In reference turfgrass plots we observed leachate volumes of 0.987 \pm 0.391 cm in 2017, 1.268 \pm 0.3919 cm in 2018, and 1.337 \pm 0.415 cm in 2019.

Weekly total water inputs explained roughly one-third (R² \sim 0.32) of the variation in weekly leachate collected from 2017 to 2019 (Fig. 2). Total observed leachate was best explained by multiple predictor variables including treatment, crop, and year (Table 3, top row). This linear model explained 39.7% of the variation in weekly leachate collected and was the best fit model from an R², adjusted R², and AIC approach. Leachate volume varied slightly across soil amendment treatments, with lowest values observed for the high municipal compost treatment and synthetic fertilizer treatments (Table 4). Leachate volume varied among crops as well, with lowest volume observed for collards, and highest volumes observed for peppers and cabbage (Table 4).

Model validation

Observed soil moisture values for garden soil with no supplemental compost addition (nofert) ranged from 10.4-20.0% in 2017, and 10.0-18.4% in 2018. Model soil moisture values had a mean absolute deviation of 2.8% in 2017 (Figure S5a) and 3.7% in 2018 (Figure S5b). Observed soil moisture values for garden soil with high municipal compost inputs ranged from 11.4-21.2% in 2017 and from 10.4-20.5% in 2018. Corresponding model soil moisture values had a mean absolute deviation of 2.7% in 2017 (Figure

S5c) and 3.5% in 2018 (Figure S5d). Observed soil moisture values for turfgrass in 2017 ranged from 7.1-19.2% (Figure S5e).

Model values tracked observed values closely and had a mean absolute deviation of 1.7%. Observed cumulative leachate values for garden soil with no supplemental compost addition totaled 153.3 mm for the 2017 growing season and 172.3 mm for 2018. Corresponding model values were 195.7 mm (Figure S6a) and 243.1 mm (Figure S6b), representing errors of 12% and 24%, respectively. Observed cumulative leachate values for garden soil with high supplemental compost addition were 62.5 mm for 2017 and 207.6 for 2018. Corresponding model values were 167.0 mm for 2017 (Figure S6c) and 219.6 mm for 2018 (Figure S6d), representing overestimates of 167% and 41%, respectively. Observed cumulative leachate values for turfgrass were 217.1 mm in the 2017 growing season and 270.3 mm for 2018. Corresponding model values were 238.6 mm in 2017 (Figure S6e) and 304.2 mm in 2018 (Figure S6f), representing errors of 10% and 12%, respectively. Modeled seasonal evapotranspiration for the garden (no compost) soil was 437 mm in 2017 and 497 mm in 2018. For the garden (high compost) soil, modeled seasonal evapotranspiration was 466 mm in 2017 and 520 mm in 2018. For turfgrass plots, modeled seasonal evapotranspiration was 242 mm in 2017 and 317 in 2018. These values are similar to values reported in Small et al. (2020) for these garden plots of 465 mm (2017) and 510 mm (2018), and values for turfgrass of 195 mm (2017) and 329 mm (2018).

Climate scenarios

Garden plots received 12-16% greater total water inputs compared to turfgrass plots, but leachate totals were 20-30% lower for garden plots across climate scenarios, due to elevated evapotranspiration, which was 50-60% higher in garden plots (Fig. 3). Within each climate scenario, difference between garden plots which received high levels of municipal compost and garden plots which received no additional compost were small relative to differences between garden plots and turfgrass. High compost garden plots had ca. 7% higher evapotranspiration, and 10-15% lower leachate totals, compared to no compost garden plots.

Comparing across climate scenarios, elevated extreme rainfall events (Scenario 3) resulted in a 4% increase in total leachate without affecting evapotranspiration. Increased magnitude of smaller rain events (Scenarios 1 and 2) led to slight increases in evapotranspiration (due to modeled relationship between ET and soil moisture), in addition to larger increases in leachate. In the baseline scenario for the simulated high municipal compost treatment, 29% of rainfall was ultimately exported as leachate, compared to 17% of irrigation inputs. For the no fertilizer treatment garden plots in the baseline scenario, 34% of rainfall was ultimately exported as leachate, compared to 21% of irrigation inputs. Elevated rainfall in the climate scenarios increased both the fraction of rainfall and irrigation inputs that ultimately ended up as leachate. In Scenario 1, where total rainfall was highest, 40% of rainfall and 24% of irrigation inputs were exported as leachate in the high municipal compost treatment, whereas in the no fertilizer garden plots, 44% of rainfall and 29% of irrigation inputs were exported as leachate (Table 5).

Discussion

Our results show that garden management practices influence the storage and fate of water, but these differences were small relative to differences between garden and reference turfgrass plots. Previous studies that have shown that the addition of organic material can increase water holding capacity (Young et al. 2014; Wadzuk et al. 2015), and our results show that the type of compost matters, with manure compost treatments maintaining highest mean soil moisture. We hypothesized that more soil water storage capacity should lead to a greater fraction of being water inputs ultimately exported as ET rather than leachate, as water should be retained longer in the soil, providing more opportunity for uptake of water by crop roots or physical evaporation. The comparison of empirical observations and model results between garden and turfgrass reference plots generally supports this hypothesis, as garden plots, which received higher water input due to irrigation, generally had lower leachate. Comparing across garden experimental treatments indicates more subtleties in the physical and biological processes controlling the fate of water. The lowest leachate values were observed in plots with municipal compost additions, and manure compost treatments were associated with higher leachate. It is possible that, by effectively retaining water in the soil, the manure compost treatments may have had a slightly lower capacity to store additional water inputs from rain events.

Some insight into the dynamics of water in garden soil can be inferred from the relationships between weekly total water inputs, soil moisture, and leachate volumes. The nonlinear relationship between weekly total water inputs and garden soil moisture (Fig. S3) shows that soils reached their maximum water holding capacity (between 0.25–0.30 mL water/mL soil) at input rates beyond 5 cm/week. The relationship between leachate volume and weekly total water inputs (Fig. 2) has an x-intercept of ~ 1 , indicating that some leachate is expected with inputs above 1 cm/week. The slope is < 0.5 , indicating that there is not a simple threshold beyond which all additional water becomes leachate, but rather, this garden soil has high water storage capacity, and more than half of additional water inputs are stored and ultimately exported through ET.

It is notable that total weekly water input variable alone explains relatively little variation in leachate volume ($R^2 = 0.32$; Table 3) and especially in soil moisture ($R^2 = 0.133$; Table 1). Experimental error accounts for some of this variation. High variation was commonly observed among replicate lysimeters. The relatively small areas of lysimeter compared to the study plots could lead to spatial heterogeneity in leachate fluxes (e.g., due to aboveground vegetation and belowground root dynamics). The simple pan (zero-tension) lysimeters used in this study are known to work reasonably well under wet conditions, but in drier soil, divergence could lead to underestimating leachate fluxes (Gee et al. 2004). Soil moisture measurements are also subject to variation due to spatial heterogeneity, error associated with conversion from instrument readings to volumetric soil water content (Fig. S1), and the differences in temporal resolution between instantaneous soil moisture measurements and cumulative weekly water inputs (e.g., a large rain event towards the end of a sampling interval would not affect soil moisture measurements collected earlier that week). More fundamentally, the lack of simple relationships between water inputs, soil moisture, and leachate underscores the complex relationships between storage and fluxes that are better captured in dynamic mass-balance model. This model, based on simple assumptions (such as no

differences between crops, and a simple relationship between soil organic matter and soil water capacity), performed reasonably well in capturing temporal dynamics and differences among treatments in observed soil moisture (Fig. S3) and cumulative leachate (Fig. S4), with a few exceptions, such as overestimating both leachate volume and soil moisture for the high municipal compost treatment in late 2017. Notably, we increased calculated ET (based on the Penman-Monteith equation, modified for common vegetable crops) by a factor of two (for both garden and turfgrass plots) to achieve good correspondence with our observed data, suggesting higher ET than would be expected from physical and biological conditions alone.

The different relative contributions of irrigation and rainwater inputs to leachate and ET (Table 5) illustrate that these different inputs have largely different fates, due to their timing, magnitude, and intensity. Irrigation occurred at moderate levels; the 60 irrigation events over three growing seasons had a median input level of 0.54 cm, with only one application exceeding 1 cm. By contrast, 62 days between 1 June 2017–31 October 2019 received rainfall in excess of 1 cm. Additionally, irrigation inputs occurred when there had not been recent rain (in contrast to the stochastic timing of rain events), so these inputs typically did not exceed the soil's capacity for storage. On the other hand, irrigation may keep soil moisture closer to the soil's water holding capacity, so that capacity to retain additional water from rain events is somewhat reduced.

Across the three growing seasons of this study, we observed ET fluxes from turfgrass and experimental gardens on similar orders of magnitude compared to other urban greenspaces (Table 6). Previous studies in urban lawns in both subtropical China and southern California found ET fluxes slightly higher than in our urban gardens (Litvak and Pataki 2016; Litvak et al. 2017; Qiu et al. 2017). These results are not particularly surprising, given the temperate climate in this study, though it may be a result of lower ET fluxes from urban gardens compared to urban lawns. Compared to other urban greenspaces such as raingardens and hedges, our gardens had lower ET fluxes (Table 6). Evapotranspiration fluxes from urban hedges may be enhanced by greater leaf area and height (Saher et al. 2020) and rain gardens are explicitly designed to infiltrate water and increase ET (Hess et al. 2017).

Conclusion

Greenspaces including rain gardens, turfgrass, and tree canopies provide essential hydrological services by increasing stormwater infiltration and retention in urban ecosystems (Zhang et al. 2015; Hoover and Hopton 2019). Our results suggest that urban gardens may function in a similar manner to engineered green stormwater infrastructure, with a high capacity for water retention, infiltration, and ET. Through the generation of ET fluxes, urban greenspace and gardens also provide some UHI mitigation benefits (Small et al. 2020). These benefits are notable because urban gardens are constructed and maintained for a variety of other purposes such as crop production, recreation, social and aesthetic goals (McDougall et al. 2019), and hydrologic ecosystem services provided by urban gardens are a secondary benefit achieved for free.

These soil management strategies can enhance hydrological services from urban greenspaces and the soil moisture pool to mitigate the urban heat island effect (Qiu et al. 2013; Zipper et al. 2017; Yang et al. 2018) or to increase garden productivity (and indirectly increase evapotranspiration, Taylor 2020). Together, these results suggest that urban garden soil management strategies may enhance urban greenspace hydrological ecosystem services through both biological and physical mechanisms.

Declarations

Ethics approval and consent to participate: This study did not use human or animal subjects

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Conflicts of interest/Competing interests: The authors declare no conflicts of interest

Availability of data and material (data transparency): All data from this study are available from EJC upon request.

Code availability (software application or custom code): All R code from this study is available from EJC upon request.

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Tables

Table 1. Best fit models for explaining variation in weekly soil moisture from 2017-2019, based on R^2 , adjusted R^2 , AIC, DAIC, and model weight. Model parameter abbreviations: Weekly soil moisture, wsm; Weekly total water inputs (irrigation plus rainfall), wtw; soil treatment, t; crop, c; year, y.

Model	R ²	Adj R ²	AIC	Δ AIC	weight
wsm~wtw+t+c+y	0.267	0.264	16779.04	0.00000	1.000000e+00
wsm~wtw+t+y	0.258	0.256	16815.13	36.09169	1.454756e-08
wsm~wtw+t+c	0.217	0.215	17022.12	243.07873	1.644839e-53
wsm~wtw+t	0.209	0.208	17052.87	273.83484	3.447619e-60
wsm~t+c+y	0.203	0.200	17093.84	314.80678	4.370964e-69
wsm~t+y	0.194	0.193	17126.05	347.00928	4.445211e-76
wsm~wtw+c+y	0.187	0.186	17158.89	379.85390	3.279244e-83
wsm~wtw+y	0.179	0.179	17188.02	408.98109	1.551978e-89
wsm~wtw+c	0.141	0.139	17366.90	587.86645	2.220359e-128
wsm~wtw	0.133	0.133	17391.65	612.61005	9.406270e-134
wsm~c+y	0.124	0.123	17441.54	662.50629	1.375900e-144
wsm ~y	0.116	0.116	17467.68	688.64109	2.907287e-150
wsm~t+c	0.091	0.089	17587.15	808.11294	3.315157e-176
wsm~t	0.076	0.075	17642.07	863.03646	3.926577e-188
wsm~c	0.015	0.014	17882.05	1103.01013	3.050662e-240

Table 2. Coefficients from the best fit model for soil moisture determined by AIC. Residual standard error: 0.02002 on 3806 degrees of freedom. Multiple R-squared: 0.4871, Adjusted R-squared: 0.4855, F-statistic: 301.2 on 12 and 3806 DF, p-value: < 2.2e-16, *** p < 0.001, * p < 0.05, Table abbreviations: Low manure, LM; High Municipal Compost, HMC; Low Municipal Compost, LMC; No fertilizer, nofert

Coefficients	Estimate	Std. error	t value	p value
(Intercept)	16.02672	0.18288	87.634	< 2e-16 ***
weeklytotalwater	0.79367	0.04374	18.146	< 2e-16 ***
2018	-0.98838	0.11673	-8.468	< 2e-16 ***
2019	0.42083	0.11031	3.815	0.000138 ***
LM	-1.44527	0.12468	-11.592	< 2e-16 ***
HMC	-0.97720	0.12993	-7.521	6.75e-14 ***
LMC	-1.49128	0.12474	-11.955	< 2e-16 ***
nofert	-2.16125	0.11911	-18.146	< 2e-16 ***
synthetic	-1.92334	0.11948	-16.098	< 2e-16 ***
cabbage	-0.62249	0.15468	-4.024	5.82e-05 ***
carrots	-0.57775	0.10133	-5.702	1.28e-08 ***
collards	-0.26751	0.11719	-2.283	0.022505 *
peppers	-0.53210	0.10133	-5.251	1.59e-07 ***

Table 3. Best fit models for explaining variation in weekly collected leachate from 2017-2019, based on R^2 , adjusted R^2 , AIC, DAIC, and model weight. Model parameter abbreviations: Weekly total water inputs (irrigation plus rainfall), wtw; soil treatment, t; crop, c; leachate, l; year, y.

Model	R ²	Adj R ²	AIC	Δ AIC	weight
l~wtw+c+y+t	0.3981	0.3966	18280.52	0.00000	9.995630e-01
l~wtw+t+y	0.392	0.391	18322.85	42.32991	6.426682e-10
l~wtw+c+y	0.395	0.3941	18295.99	15.47027	4.370030e-04
l~wtw+y	0.3889	0.3885	18338.06	57.54532	3.191561e-13
l~wtw+t+c	0.3366	0.3352	18762.19	481.67464	2.543849e-105
l~wtw+c	0.3341	0.3335	18770.41	489.89271	4.177909e-107
l~wtw+t	0.3249	0.324	18841.45	560.92659	1.570904e-122
l~wtw	0.3225	0.3224	18848.78	568.25765	4.020032e-124
l~t+c+y	0.07076	0.06876	20876.45	2595.93587	0.000000e+00
l~c+y	0.06778	0.06669	20882.86	2602.34289	0.000000e+00
l~t+y	0.06476	0.06348	20901.41	2620.88774	0.000000e+00
l~y	0.06178	0.06141	20907.71	2627.18966	0.000000e+00
l~t+c	0.01019	0.008448	21195.76	2915.24382	0.000000e+00
l~c	0.008021	0.007245	21196.98	2916.45995	0.000000e+00
l~t	0.00212	0.001144	21229.35	2948.82771	0.000000e+00

Table 4. Coefficients from the best fit model for weekly leachate determined by AIC
Residual standard error: 1.508 on 4979 degrees of freedom. Multiple R-squared: 0.3981,
Adjusted R-squared: 0.3966, F-statistic: 274.4 on 12 and 4979 DF, p-value: < 2.2e-16, *** p
< 0.001, * p < 0.05, Table abbreviations: Low manure, LM; High Municipal Compost, HMC;
Low Municipal Compost, LMC; No fertilizer, nofert

Coefficients	Estimate	Std. error	t value	p value
(Intercept)	-1.071863	0.078208	-13.705	< 2e-16 ***
weeklytotalwatercm	0.457690	0.008734	52.406	< 2e-16 ***
2018	0.979993	0.059057	16.594	< 2e-16 ***
2019	1.296135	0.058498	22.157	< 2e-16 ***
LM	-0.192067	0.074084	-2.593	0.009555 **
HMC	-0.297383	0.077139	-3.855	0.000117 ***
LMC	-0.244155	0.074084	-3.296	0.000989 ***
nofert	-0.221931	0.070730	-3.138	0.001713 **
synthetic	-0.325802	0.070730	-4.606	4.20e-06 ***
cabbage	0.232162	0.092192	2.518	0.011825 *
carrots	0.116438	0.060354	1.929	0.053756
collards	-0.184489	0.069690	-2.647	0.008140 **
peppers	0.279190	0.060354	4.626	3.82e-06 ***

Table 5. Leachate and ET fluxes originating from precipitation and from irrigation, for high municipal compost (HMC) and no fertilizer treatment garden plots, for the four climate scenarios. S0 = baseline precipitation, S1 = 30% increase in magnitude for all precipitation events, S2 = 30% increase in magnitude for spring and fall precipitation events, S3 = 25% increase in magnitude of precipitation events exceeding 5.08 cm. Values are reported in cumulative mm over the 880 day simulation period.

Treatment	Scenario	Cumulative precipitation (mm)	Cumulative irrigation (mm)	Cumulative leachate from rain (mm)	Cumulative leachate from irrigation (mm)	Cumulative ET from precipitation (mm)	Cumulative ET from irrigation (mm)
High Municipal compost	S0	1897	328	550	55	1322	274
	S1	2466	328	995	79	1446	249
	S2	2155	328	758	63	1373	264
	S3	1923	328	576	55	1324	273
No fertilizer	S0	1897	328	644	69	1236	258
	S1	2466	328	1095	94	1353	234
	S2	2155	328	853	78	1284	249
	S3	1923	328	963	89	1296	239
Turfgrass	S0	1897	0	889	0	1002	0
	S1	2466	0	1372	0	1089	0
	S2	2155	0	1100	0	1050	0
	S3	1923	0	916	0	1002	0

Table 6. Daily ET fluxes from various urban greenspaces.

Greenspace type	Greenspace landcover	Location	ET (mm)	Temporal ET units	Reference
Urban gardens	Raised garden beds with crops	St. Paul, MN	1.8	Daily; 3 growing seasons	This study
Urban lawn	Turfgrass	St. Paul, MN	1.1	Daily; 3 growing daily	This study
Urban lawn	Not provided	Subtropical China	2.7		Qiu et al. 2017
Urban lawn	Not provided	Los Angeles, CA	5.5	Warm season daily (June, August)	Litvak and Pataki 2016
Urban lawn	Not provided	Los Angeles, CA	2.5	Cool season daily (Jan, Feb)	Litvak and Pataki 2016
Urban lawn	53% lawn, 29% tree, 15% impervious	Twin Cities, MN	2.7-3.1	Summer daily	Peters et al. 2011
Urban landscape	70% of ET from turf, 30% trees	Los Angeles, CA	4.3	June daily	Litvak et al. 2017
Urban landscape	70% of ET from turf, 30% trees	Los Angeles, CA	1.5	December daily	Litvak et al. 2017
Turfgrass	Not provided	Across USA	5-6	Daily warm season grass	Romero and Dukes 2016
			7-10	Daily cool season grass	Romero and Dukes 2016
Hedges	Not provided	Subtropical China	8	Daily warm season	Zou et al. 2019
Rain garden	Sandy loam media	Philadelphia, PA	4	Daily cool season daily	Zou et al. 2019
			2.9-4		Hess et al. 2017

Figures

Soil moisture and weekly water inputs, 2017–2019

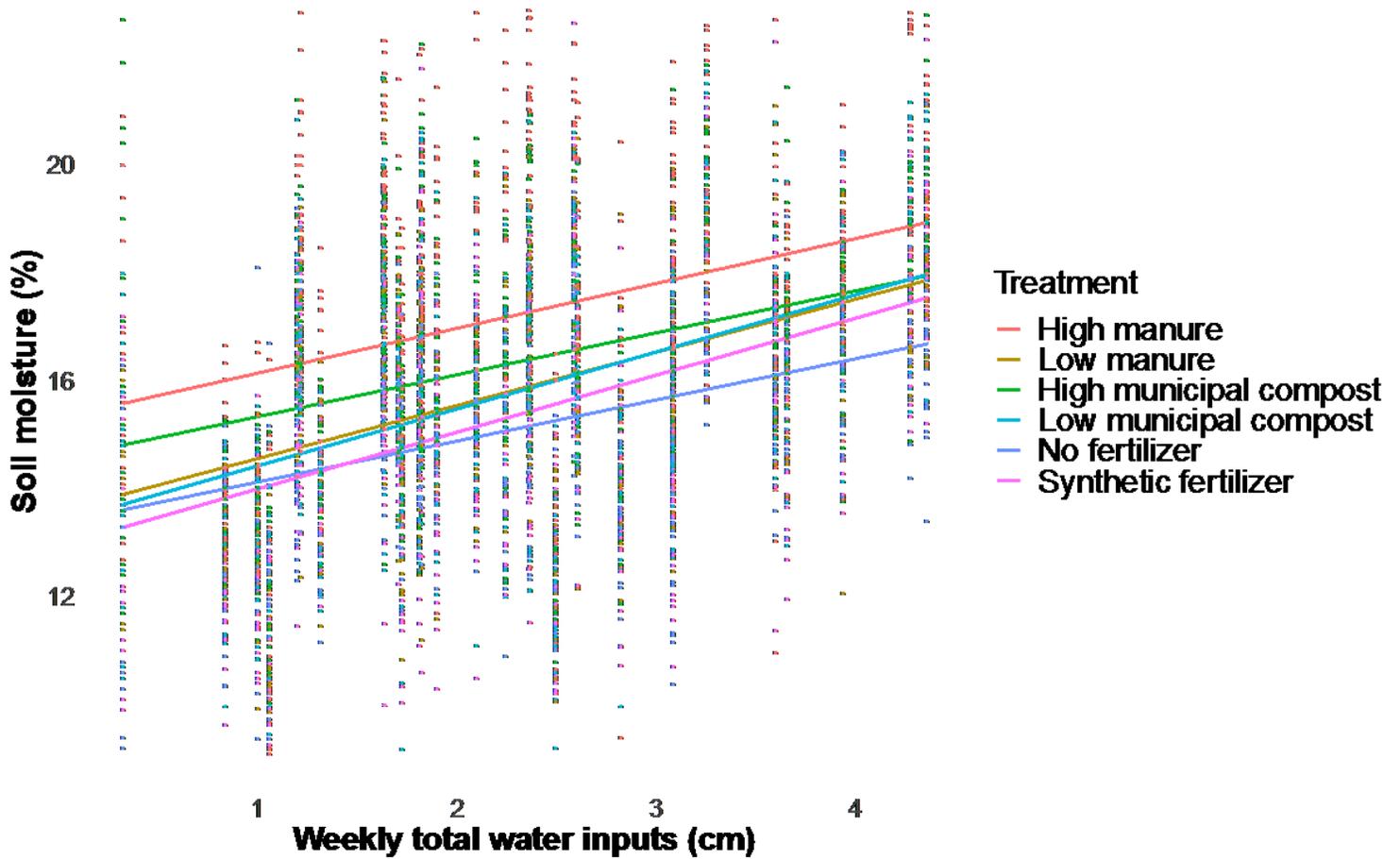


Figure 1

Soil moisture as a function of weekly total water inputs grouped by treatments. Most weeks of the experiment total water inputs were less than 5 cm. Soil moisture was weakly correlated with weekly total water inputs and treatment effects on soil moisture were evident in soil moisture values clustering. Figure containing full range of total weekly water inputs greater than 5 cm can be found in the appendix (Figure S5).

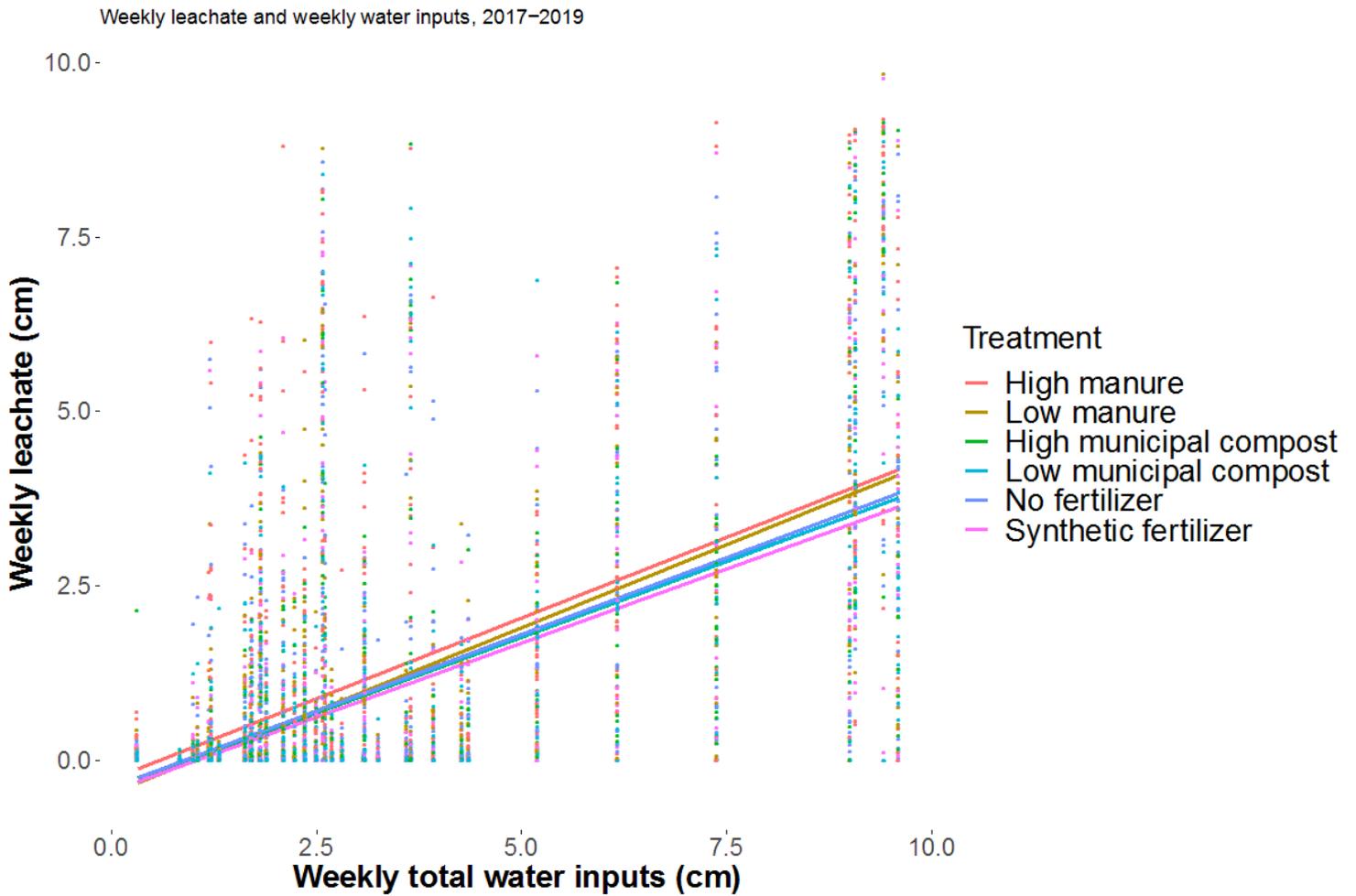


Figure 2

Weekly leachate collected as a function of total weekly water inputs across each year of the study. Weekly leachate is positively correlated with total water inputs for each year and weekly water inputs describe roughly one-third of the variation within weekly leachate collected. There were no differences between treatments or crops in weekly leachate collected.

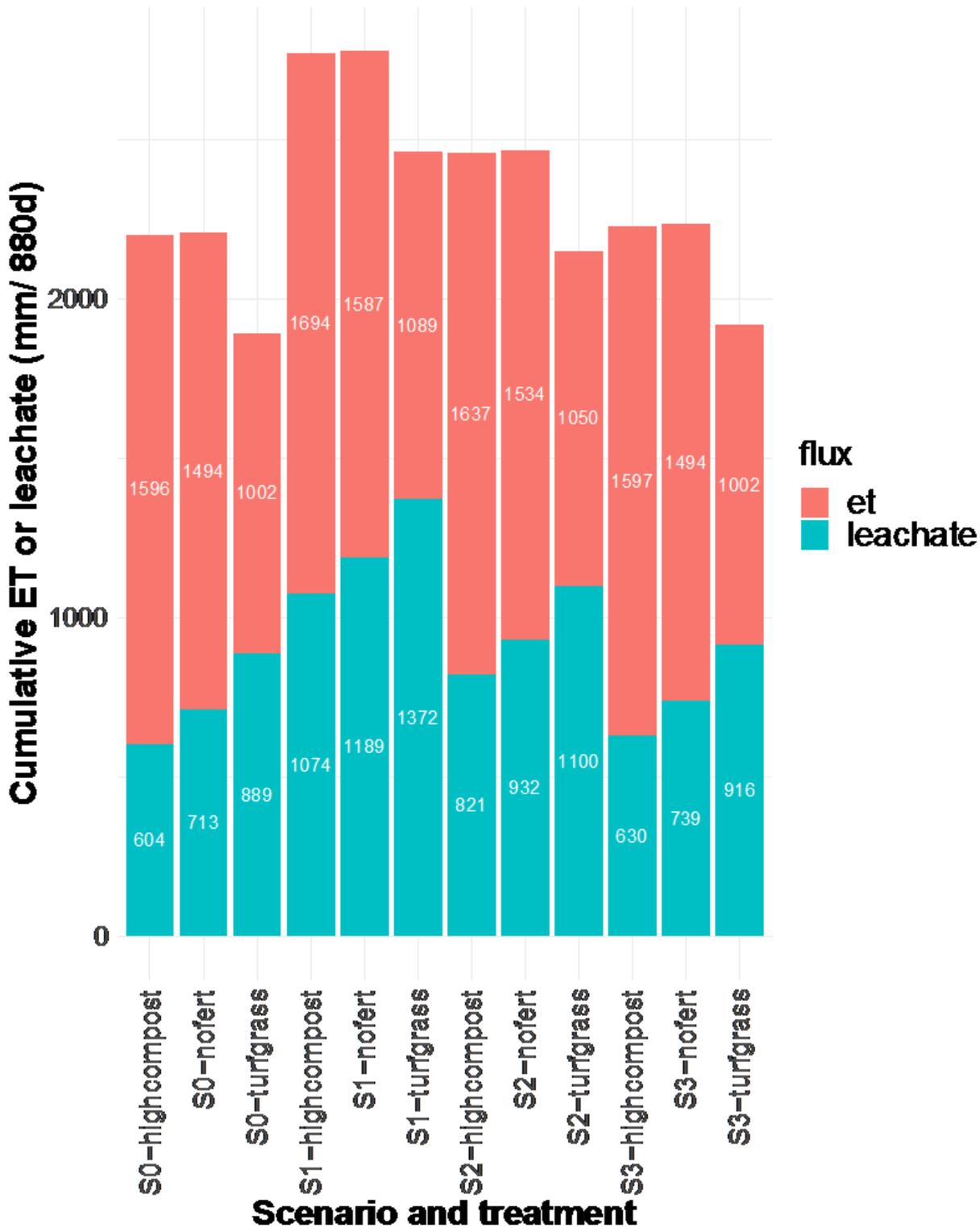


Figure 3

Simulated cumulative ET and leachate over three growing seasons from turfgrass, garden plots with no supplemental soil amendments (nofert treatment), and high municipal compost inputs, under baseline climatic conditions (S0) and three elevated rainfall scenarios (S1, S2, S3). See text for full scenario description.

Supplementary Files

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