

ORIGINAL ARTICLE

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Phosphorus recycling and loss from compost-amended urban gardens: Results from a 7-year study

Gaston E. Small^{1,2}  | Paliza Shrestha¹ | Carolyn Zeiner¹  | György Barabás^{3,4} | Geneviève Suzanne Metson^{3,5}

¹Biology Department, University of St. Thomas, Saint Paul, Minnesota, USA

²Department of Earth, Environment, and Society, University of St. Thomas, Saint Paul, Minnesota, USA

³Ecological and Environmental Modeling Division, Department of Physics, Chemistry, and Biology (IFM), Linköping University, Linköping, Sweden

⁴Institute of Evolution, Centre for Ecological Research, Budapest, Hungary

⁵Department of Geography and Environment, Social Sciences Centre, The University of Western Ontario, London, Ontario, Canada

Correspondence

Gaston E. Small, Biology Department,
University of St. Thomas, Saint Paul, MN,
USA.

Email: gaston.small@stthomas.edu

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Abstract

Urban vegetable gardens provide an opportunity to recycle nutrients from food waste back into the human food system through the application of compost. However, a reliance on compost for soil fertility can lead to excess phosphorus (P) inputs that can build up in garden soil and potentially be exported via leachate or runoff. We report the results of a 7-year experiment in a campus research garden in which replicated raised-bed garden plots received manure-based compost or municipal compost that was applied at a higher rate targeted to meet crop nitrogen demand or a lower rate targeted to meet crop P demand. Control plots received either no soil inputs or targeted synthetic fertilizer. Higher input treatments for both types of composts showed steadily increasing concentrations of soil plant-available P, with a corresponding increase in leachate phosphate concentration. For both higher input compost treatments, approximately 30% of P added as compost was recovered in harvested crops over the 7-year period, compared to >88% in the lower input compost treatments. In both high- and low-input manure compost treatments, export of P as leachate accounted for approximately 10% of total P input, compared to 4% for the municipal compost. Over the 7-year study period, P exported as leachate ranged from 0.8 g P/m² in the no-input treatments to 6.5 g P/m² in the higher input manure compost treatments. These results show that tradeoffs are not inevitable as targeted compost applications can lead to high yield and low leachate export.

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1 | INTRODUCTION

1.1 | Opportunities and challenges inherent in recycling compost-derived phosphorus

Urban ecosystems are characterized by large throughflows of material and a low degree of internal cycling. Closing nutrient cycling in urban ecosystems has been identified as essential to sustainability (Burger et al., 2012; Childers et al., 2011). Of particular importance, geopolitical access to mineral phosphate fertilizers may constrain agricultural production in the coming century (Brownlie et al., 2021, 2023), and urban waste streams could, and should, become important sources of this nutrient in the future (Baker, 2011; Metson et al., 2022).

One important pathway by which cities may expand phosphorus (P) recycling is through the composting of municipal organic waste and subsequent application of this compost in urban and peri-urban agriculture. Many regional and state governments have adopted ambitious goals mandating the diversion of organic waste entering landfills with the goal of reducing methane emissions (e.g., California's waste diversion law, SB 1383), resulting in an increasing supply of compost generated in urban centers. More than one-third of the 2 million farms in the United States are located within metropolitan areas, and these urban and peri-urban farms account for >35% of fruit and vegetable production in the country (Kaufman & Bailkey, 2000; Rogus & Dimitri, 2014; Smit et al., 1996; Sommers & Smit, 1994), creating potential for large-scale nutrient recycling.

In contrast to global agricultural lands for which, on average, soil P stocks are slowly declining (Alewell et al., 2020), several factors are likely to contribute to a buildup of P in soils in urban and peri-urban farmland. First, the transportation of compost is energy intensive and costly, constraining its application within a limited radius of urban areas (Harrison et al., 2020). Assimilating the amount of P supplied by the entirety of a city's organic waste stream requires an area of farmland several times greater than the geographic footprint of the city itself (Metson & Bennett, 2015), and depending on economic thresholds for transporting compost, some larger urban areas may not have sufficient available nearby farmland (Harrison et al., 2020). This constraint may result in overapplication of compost-based P in farms within this radius, similar to overapplication of animal manure that is common in fields around livestock operations (Tarkalson & Mikkelsen, 2003; Whalen & Chang, 2001). A second biophysical constraint stems from the fact that compost typically has a low nitrogen:phosphorus (N:P) ratio relative to crop demands (Kleinman et al., 2007, 2011; Mikkelsen & Bruulsema, 2005), and as a result, the application of compost to meet crop N demand leads to inputs of excess P. A third factor contributing to overapplication of compost P is the perception among many urban vegetable growers that high compost inputs are beneficial and sus-

Core Ideas

- Compost applied to urban gardens to meet crop nitrogen demand results in excess phosphorus inputs.
- After 7 years, experimental plots receiving higher inputs of manure compost had high P leachate losses.
- Plots receiving higher inputs of municipal compost had highest levels of plant-available P.
- Compost inputs targeted for crop P demand had high yield and minimized P loss from leachate.

tainable. This perception, combined with a general lack of regulatory and economic disincentives against overapplication of P, leads to P inputs in urban gardens at rates 10–100 times higher than P recovered by crops (Abdulkadir et al., 2015; Metson & Bennett, 2015; van de Vlasakker et al., 2022).

One potential consequence of long-term P overapplication is that excess plant-available P can be exported from soils as leachate or surface runoff, potentially contributing to eutrophication in nutrient-sensitive freshwater ecosystems. While P can be retained by mineral complexes in soils, long-term high P inputs can exceed the capacity of soils to retain excess P, leading to elevated P export in drainage water, as has been observed in the century-long Broadbalk Experiment (Heckrath et al., 1995). To date, very few studies have quantified P loss from leachate in urban agriculture systems (van de Vlasakker et al., 2022). These reported values are highly variable, spanning three orders of magnitude, and are not consistently related to P input rates. This variability in P loss across studies may be due to the capacity of different soils to retain excess P.

Because there are both potential consequences and benefits to nutrient recycling from compost-based urban agriculture, inherent tradeoffs may emerge. A management strategy aimed at maximizing crop yield may ultimately result in higher P leachate rates. A management strategy targeted at optimizing P recycling efficiency or minimizing P leachate could result in depressed yields and ultimately recycle a lower mass of P. Understanding these tradeoffs requires long term experimental studies to measure the dynamics of P storage, recycling, and loss in compost-based urban agricultural systems.

1.2 | Results from previous studies in Minneapolis-Saint Paul

Our previous work in Minneapolis-Saint Paul, MN, documented high compost application rates by many urban gardeners (median application rate = 300 kg P/ha) and low

nutrient P-use efficiencies (median value of 2.5%; Small, Shrestha, et al., 2019). Garden soils typically had levels of plant-available P far higher than recommended levels, increasing with garden age (Small, Shrestha, et al., 2019), evidence of P buildup over time. In replicated raised bed garden plots, we found that typically high compost inputs can result in leachate losses similar in magnitude to crop uptake (Small et al., 2018). Native soils below established garden plots showed P accumulation relative to adjacent soils indicating the transport of excess P along hydrologic flowpaths (Small, Osborne, et al., 2019). The combination of high garden density and high compost inputs coupled with the high density of impervious surfaces on the landscape indicates that urban gardens could be a significant source of P export in urban watersheds (Small et al., 2023).

To better understand how compost quality and application rate affect the rates of nutrient recovery by crops and nutrient export by leachate in urban gardens, we have conducted a multi-year experiment using replicated raised bed garden plots at the University of St. Thomas in Saint Paul, MN. Plots received annual inputs of manure-based compost (composted cow manure from a dairy farm, sourced by a local landscaping company) or municipal compost (a mixture of yard waste, food scraps, and other compostable products, provided by a regional composting facility). These composts were selected because they are readily available and are commonly used in backyard gardens, community gardens, and urban farms in Minneapolis-Saint Paul (Small, Shrestha, et al., 2019). Composts were added either at a relatively higher input rate targeted to meet crop N-demand (therefore resulting in excess P) or at a lower input rate targeted to meet crop P-demand (supplemented with additional inorganic N fertilizer). Notably, the higher input rates used in this experiment are lower than the median compost application rates we previously documented across vegetable gardens and urban farms in Minneapolis-Saint Paul (Small, Shrestha, et al., 2019). Control treatments included plots that received inputs of inorganic N and P, and plots that received no inputs of any compost or fertilizer. We previously published nutrient budget results from the first 2 years of this experiment (Shrestha et al., 2020). After 2 years of soil amendments, there was no significant treatment effect on crop yields, as mineralization of organic matter in the soil from before the start of the experiment continued to meet crop nutrient demand in the no-input control treatment. The fraction of P in harvested crops relative to compost P inputs ranged from 68% to 69% for the lower input treatments, and from 16% to 29% for the higher input treatments. Higher input compost treatments resulted in P leachate export rates that were 46% higher (for municipal compost) and 70% higher (for manure compost) compared to the no-compost control treatment. Notably, these P leachate fluxes represented a small fraction of total P inputs (0.7%–2.8%) and were an order of magnitude lower than we had

documented in a previous study that used higher compost input rates more typical of urban gardeners (Small et al., 2018). Those results underscored potential tradeoffs between P recycling and loss in urban gardens, but also suggested that moderate levels of compost P inputs to gardens largely result in P retention by garden soils.

1.3 | Goals of the current study

Here, we reanalyze results of this study after 7 years of treatment application. There are several reasons why results may vary both qualitatively and quantitatively over this longer timescale. First, relatively high yield was sustained in the no-compost control treatment in the early years of the study, but the initial store of organic matter in the garden soil should decline over time, potentially resulting in lower crop yields due to N limitation and, in turn, lower recovery of P in the soil. Second, rapid mineralization rates and high microbial phosphatase activity in plots receiving high inputs of manure compost (Zeiner et al., 2024) may exceed uptake rates of crops, leading to a saturation of the capacity of the soil to retain the resulting inorganic P and resulting in higher rates of P export via leachate. Municipal compost, by contrast, produces inorganic P at a slower rate that more closely aligns with crop uptake rates, leading to lower P leachate rates and higher rates of P recycling efficiency (Shrestha et al., 2020). Additionally, changes in soil organic matter over time among these treatments are likely to affect water retention, and thereby indirectly affect rates of P export via leachate. From the first three seasons of this study, the higher input compost treatments maintained higher soil moisture and resulted in lower leachate volumes (Chapman et al., 2022), presumably because moisture remained closer to field capacity. After 7 years of compost inputs, differences in organic matter among treatments should continue to increase, potentially magnifying differences in the fate of water and P transport. We hypothesize that higher inputs of manure compost will show increasingly large rates of P export as leachate over time, whereas lower inputs of municipal compost will result in highest P recycling efficiency and low P leachate losses.

2 | METHODS

2.1 | Site description

This study took place at the campus research garden at the University of St. Thomas in Saint Paul, MN (44°56'17"N, 93°11'46"W). The average annual temperature is 8.3°C, and the mean annual precipitation is 803 mm (Small et al., 2020). The research garden was established in 2011 and consists of 32 raised beds measuring 4 m² and ca. 0.3 m deep (Figure 1). The soil texture is approximately 60% sand, 25% silt, and



FIGURE 1 Campus research garden where this study was conducted. Each of the 32 4 m² raised beds were assigned to one of six soil amendment treatments during the 7-year study. Each raised bed was divided into four 1 m² subplots, in which peppers, carrots, bush beans, and cabbage (year 1) or collards (years 2–7) were grown.

15% clay (Table S1). The depth of the water table below the research garden is approximately 3–4 m. From 2011 to 2016, the garden was used for a series of single-season experiments, and compost was added to plots annually. Prior to the start of the current experiment in 2017, soil from all raised-bed garden plots was removed, homogenized, and redistributed. This soil had an organic matter content (loss on ignition method) of 9.4%, a plant-available phosphorus concentration (Bray P-1) of 75 parts per million (ppm), an available potassium concentration (NH₄OAc extraction) of 95.5 ppm, and a nitrate concentration of 7.4 ppm.

2.2 | Experimental design

Each plot was randomly assigned one of six treatments:

- a higher level of manure compost targeted to meet crop N demand;
- a lower level of manure compost targeted to meet crop P demand, supplemented with additional inorganic N fertilizer;
- a higher level of municipal compost targeted to meet crop N demand;
- a lower level of municipal compost targeted to meet crop P demand, supplemented with additional inorganic fertilizer;
- inorganic N and P corresponding to estimated crop N and P demand;
- a control treatment with no fertilizer applied.

Compost and fertilizer input rates were determined based on the estimated plant N and P demands of the four crops

used in this experiment. Compost was acquired from the same vendors each year and applied based on volume, according to calculated application rates required to meet crop nutrient demand prior to the start of the experiment (Tables S2 and S3). The physical and chemical properties of the two compost types are reported in Table 1. Because compost bulk density and nutrient concentrations varied somewhat among years (Table S4), actual nutrient input rates varied year to year.

Inorganic N fertilizer (26-0-2) was used in the synthetic fertilizer control treatment and in the low-input compost treatments. Inorganic P fertilizer (0-16-0) was used in the synthetic fertilizer control treatment. Compost and inorganic P fertilizer were applied at the start of the growing season (late May) to the top of the garden soil, and during planting, they were mixed into the top 10 cm of soil. Inorganic N fertilizer was applied on top of the soil across five biweekly applications during June and July.

2.3 | Soil CO₂ flux

Soil carbon dioxide (CO₂) flux was measured as an indicator of the rate of microbial mineralization of soil organic matter. Soil CO₂ flux was measured on 31 different sampling dates throughout the 7-year study period (typically every 2–4 weeks during the growing season; no measurements were taken in 2020 and only one set of complete measurements was taken in 2023) using a LI-8100A Automated Soil CO₂ flux system (Figure S1). Measurements were made in the center of all “A” subplots on each sampling date, measuring a soil area of 318 cm².

2.4 | Soil analysis

Soil samples were collected from the top 10 cm of subplots, once at the beginning of the current study (prior to the first compost application), once at the end of the first season, and for years 2–6, at biweekly intervals from June to October, and during year 7, at monthly intervals, using composite samples for each treatment collected from “A” subplots. Soil samples were analyzed for organic matter (loss-on-ignition method), pH, nitrate (NO₃⁻), available potassium (NH₄OAc extraction), and Bray P-1 at the University of Minnesota Research Analytical Lab. A subset of samples were additionally measured for ammonium (NH₄⁺) and for total P. Specific methods are described in detail in Shrestha et al. (2020).

2.5 | Crop production

The crops used in this study represented four different plant families and are commonly grown in urban farms and

TABLE 1 Physical and chemical properties of the two compost types (manure compost and municipal compost) used in this study. Element concentrations are reported as percentage (%) by dry weight. The carbon:nitrogen (C:N) ratio is reported as mass ratio.

Compost type	Bulk density (g dry mass/L)	Total organic C (%)	Total N (%)	C:N ratio	Total P (%)	Total K (%)
Manure	96.7	38.73	1.16	33.66	0.24	0.57
Municipal	375.5	22.22	1.38	16.11	0.19	0.64

Note: Values reported here are averaged across the study years; annual values are reported in Table S4.

vegetable gardens: bell peppers (*Solanaceae*); bush beans (*Fabaceae*); carrots (*Apiaceae*); and cabbage (year 1) or collards (years 2–6) (*Brassicaceae*). We used X3R Red Knight (F1) pepper seeds, E-Z Pick Organic bean seeds, Nectar Organic Pelleted (F1) carrot seeds, Omero (F1) cabbage seeds, and Flash collard seeds acquired from Johnny's Selected Seeds. Peppers, beans, cabbages, and collards were started in a greenhouse and transplanted after reaching a height of 10 cm. Carrots were planted directly from seeds. Peppers, cabbages, and collards were planted in two rows of three plants (6 plants/m²), beans were planted in two rows of six plants (12 plants/m²), and carrots were planted in three rows of 20 plants (60 plants/m²). Seedlings that died during the first 2 weeks of the experiment were replaced. The four crops were rotated annually in a clockwise direction within the plots.

Plots received ambient rainfall and supplemental irrigation, maintaining soil moisture >15% during the first half of each growing season (Figure S2). Soil moisture was typically measured 3 days per week from June to August using a handheld soil moisture meters (DSMM500, General Tools & Instruments). We have previously compared these values to gravimetric measurements (Chapman et al., 2022).

When irrigation was required, we watered evenly over the 4 m² raised beds for a set time (typically 30–45 s) in each plot and estimated the volume of water added by measuring the amount of time required to fill a 10 L bucket at that flow rate. Weeds were removed from each plot approximately once per week. Insect pests (e.g., *Popillia japonica*) were removed by hand when encountered.

Crops were harvested between early July and early October. Beans, peppers, and collards were harvested weekly; cabbages (during year 1) and carrots were harvested over one or 2 days each season. Wet mass was recorded for all harvested crops (including stems and leaves for carrots) removed from each subplot (Figure S1). Each season, a subsample of plant material (homogenized for each treatment × crop combination) was dried and analyzed for total P at the University of Minnesota Research Analytical Laboratory. Briefly, total P was analyzed by digesting in HNO₃ using a modified Miller Digest method, followed by analysis by inductively coupled plasma atomic emission spectrometry.

Phosphorus removed through harvested crops per plot was calculated as:

$$C_P = C_{wm} \times (C_{dm} : C_{wm}) \times C_{\%P} \quad (1)$$

where C_P is crop P (g P/m²/year), C_{wm} is crop wet mass (g/m²/year), $C_{dm} : C_{wm}$ is the crop dry mass to wet mass ratio, and $C_{\%P}$ is crop P content (g P/100 g dry mass).

2.6 | Meteorological and leachate measurement

Rainfall data were collected at hourly intervals in the research garden beginning in June 2017. Rainfall was measured using an ECRN-50 rain gauge (Part # 40,655, METER; Figure S1).

Leachate was measured using custom-designed zero-tension lysimeters installed in the center of each 1 m² subplot (128 total). Lysimeters consisted of an 11.8-cm diameter-plastic funnel (0.0109 m²) secured to a 1-L wide-mouth plastic Nalgene bottle. Tygon tubing (inside diameter of 0.2 cm) was extended from the base of the bottle through the funnel to above the soil surface for leachate removal. Rock wool was wedged around the Tygon tubing in the funnel opening to prevent soil particles from entering the bottle. Lysimeters were buried so that the top of the funnel was 0.3 m below the soil surface (below the rooting zone of the crops).

Leachate water was removed from each lysimeter every week from late May to mid-October using a 50-mL polypropylene syringe (Figure S1). Total volume was recorded, and a subsample (5–20 mL, depending on the available volume) was transferred to a plastic scintillation vial for subsequent nutrient analysis. Water samples were typically refrigerated and analyzed within 48 h, but some samples were frozen for later analysis. Leachate phosphate (PO₄³⁻) concentrations were analyzed using a Hanna Instruments Low Range Phosphate Portable Photometer (HI96713).

Leachate P flux was calculated as:

$$L_P = \sum_{i=1}^n (L_v \times L_{[PO_4-P]}) / L_A \quad (2)$$

where L_P is seasonal leachate P flux (g PO₄-P/m²), n is the number of weekly sampling events (ca. 22 per season), L_v is weekly lysimeter water volume (L), $L_{[PO_4-P]}$ is phosphate concentration in each lysimeter sample (g PO₄-P/L), and L_A is the area of the lysimeter funnel (m²). The volume of leachate water was divided by the lysimeter area to report the amount of drainage (cm).

For lysimeter observations in which PO_4^{3-} -P concentrations were missing (typically in cases where less than 5 mL of leachate was collected), we estimated PO_4^{3-} -P concentrations using a seasonal treatment mean specific to each crop to use for seasonal leachate flux calculations (analyses of leachate concentration only included direct measurements). Approximately 25% of all values for leachate PO_4^{3-} -P concentrations used in flux calculations (4266 out of 17,974 total observations) were estimated. However, because these were mostly low-volume samples, the total leachate PO_4^{3-} -P flux represented by interpolated values is low (<7%).

We did not make year-round measurements (lysimeters were sampled from late May to mid-October), so our calculated seasonal leachate flux values underrepresent the annual leachate flux. However, we note that the soil is typically frozen from November to April, so little to no leachate would be expected during those months. One of the study plots contained a Meter Drain Gage G3 lysimeter that recorded year-round hourly changes in leachate volume during the initial years of the experiment. From June 1, 2017, to May 31, 2018, 98% of total leachate (1090 mm out of 1114 mm) occurred during the time period during which the 128 lysimeters were being sampled each week. Therefore, it is likely that reported leachate fluxes measured during the growing season approximate annual fluxes.

2.7 | Data analysis

Temporal trends in soil CO_2 flux, soil organic matter, soil Bray P-1, and leachate PO_4^{3-} concentrations were plotted using the *geom_smooth* function in the *ggplot2* package (Wickham, 2016) in R Statistical Software (v4.3.1; R Core Team, 2021), which generates smoothed conditional means using the locally estimated scatterplot smoothing method, to allow for visual detection of breakpoints or other nonlinear behavior.

We visually inspected plots of crop yield (wet mass), leachate water volume, and leachate PO_4^{3-} fluxes by year, crop, and treatment, both untransformed (Figures S3–S5) and transformed (e.g., log), to identify potential patterns for statistical analyses (i.e., visual inspection for meaningful variables to avoid overfitting models blindly). Because data were strongly heteroscedastic, we used weighted regression, with weights being the inverse of the variances for each combination of the predictors. Because visual analysis showed that the dependence of cumulative leachate PO_4^{3-} on crop type was weak, we also considered a simplified model (leachate $\text{PO}_4^{3-} \sim \text{treatment} + \text{year} + \text{treatment} \times \text{year}$) (Figure S6), and following inspection of diagnostic plots (Figures S7–S10), applied AIC and BIC scores to decide between the models (Table S5). Every model fit was also inspected using four-plot diagnostics, generated using the *autoplot* function

from the *ggfortify* package (Tang et al., 2016) in R (R Core Team, 2023).

Based on the findings of significant treatment effects from the weighted regression models, we performed post hoc tests using both *t*-tests and nonparametric Wilcoxon rank-sum tests. The former method tests the null hypothesis of equal means between two distributions; the latter tests the null hypothesis of equal medians. These tests were conducted manually in R between all pairs of groups of data, using the *t.test* and *wilcox.test* functions. In the case of leachate PO_4^{3-} flux, we compared fluxes across treatments for each study year. For water fluxes, the year was by far the most important predictor, limiting the usefulness of comparisons among treatments or crops. For crop yields, the difference among crop types is intuitive as different vegetables have different seasonal yields. We examined differences in yields across treatments separately for each year $\times$ crop combination. The *p*-values were adjusted for multiple comparisons using the False Discovery Rate correction and were set at a significance of 0.05.

Annual P budgets were calculated for each of the six experimental treatments by calculating the total P applied as compost or fertilizer (see Section 2.2), harvested in crop biomass (Equation 1), and exported as leachate (Equation 2). Values were averaged across subplots (i.e., across different crops) to compare treatment effects over time. Cumulative P inputs and exports by crop harvest and leachate were calculated across the seven growing seasons by adding all seven seasons of data together for each of the six treatments.

Project data are archived on the EDI data portal (Small & Shrestha, 2023).

3 | RESULTS

3.1 | Soil CO_2 flux

During the first month after compost application, soil CO_2 flux from the high-input manure treatment was two to four times higher compared to values from other treatments, ranging from 4 to 8 $\mu\text{mol CO}_2/\text{m}^2/\text{s}$ (Figure 2). Values typically converged after 2 months. Measured CO_2 flux values across other treatments did not show consistent seasonal trends.

3.2 | Soil organic matter

Soil organic matter diverged over time across treatments from an initial value of 9%. The no-input control decreased gradually to approximately 7% over the 7 years (Figure 3). Treatments that received high inputs of manure compost and municipal compost increased to approximately 15% by year 7. Lower inputs of manure compost and municipal compost

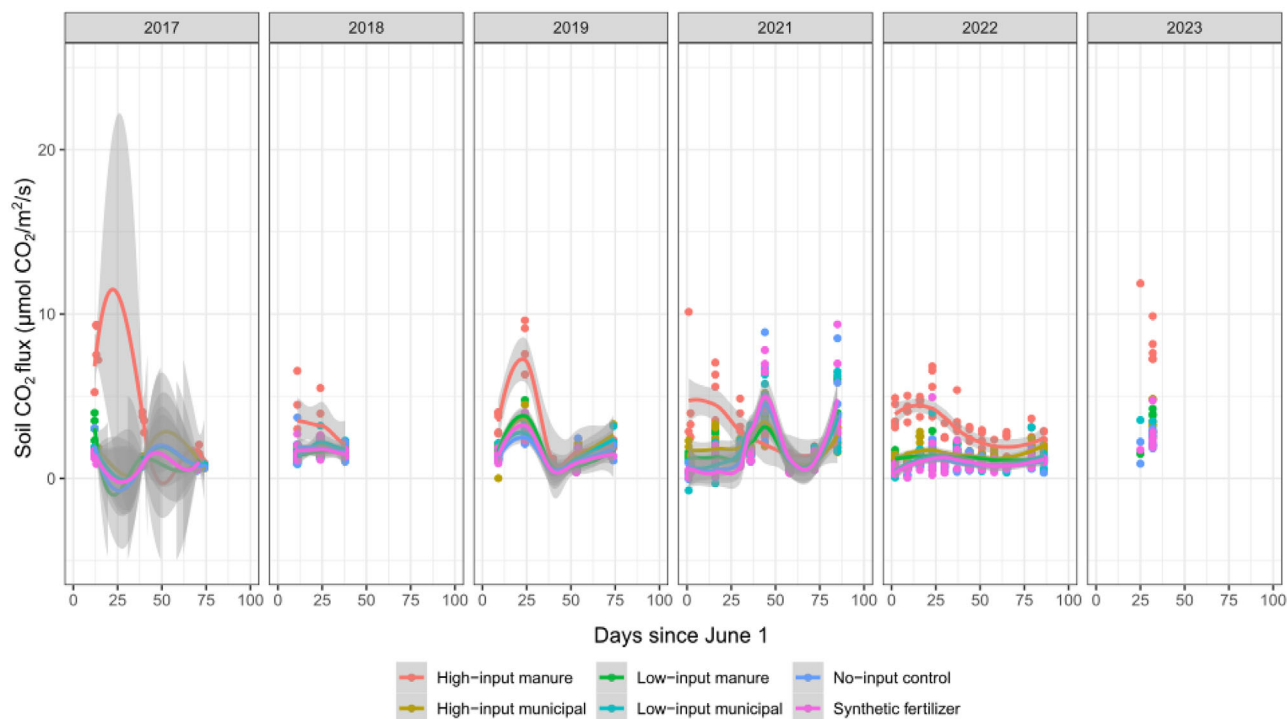


FIGURE 2 Soil CO₂ flux from each of the six experimental treatments over 7 years (no data were collected in 2020). Compost was applied each year in the final week of May. Lines are smoothed conditional means using the locally estimated scatterplot smoothing (LOESS) method. Shaded areas represent 95% confidence intervals.

resulted in relatively constant soil organic matter during the study period, within 1% of initial values.

3.3 | Soil plant-available phosphorus

Initial soil plant-available P (measured as Bray P-1) values were 75 ppm. Both the no-input control treatment and the low-input manure compost treatment showed gradual declines over the 7 years, reaching approximately 50 ppm (Figure 4). The high-input municipal compost treatment resulted in the highest levels of plant-available P, with year 7 mean values of 120 ppm. The high-input manure compost treatment increased to approximately 100 ppm after three seasons but showed a slight decline from years 4–7 (Figure 4). Both the low-input municipal compost treatment and the synthetic fertilizer treatment maintained concentrations of plant-available P similar to initial values over the 7-year study period (Figure 4).

3.4 | Other soil nutrients

Soil NO₃-N was lowest (Figure S3) in the no-input control treatment and in the high-input manure compost treatment, with values typically ranging from 5 to 15 ppm (Figure S11). Soil NH₄-N typically ranged from 0 to 10 ppm, declining over time in most treatments (Figure S12). We note that the

two low-input compost treatments and the synthetic fertilizer treatment received regular inputs of N fertilizer during the growing season.

Soil available K was highest in the high-input municipal compost treatment, with values ranging from 500 to 1000 ppm (Figure S13). High-input manure compost and low-input municipal compost generally had available K levels from 200 to 500 ppm, and the other three treatments ranged from 50 to 100 ppm (Figure S13). Soil pH remained circumneutral during the study, with 95% of observations ranging from 6.6 to 7.8 (Table S6).

3.5 | Crop yield

Crop yield for three of the four crops (beans, carrots, and peppers) declined over the 7-year study period (Figure 5). However, this trend was uneven across treatments (Table S7). Pairwise comparisons based on *t*-tests (Figure S14) show that the no-input control treatment had lower yields than one or more of the compost treatments for beans (years 3–7), collards (years 2, 3, and 5), carrots (years 6–7), and peppers (years 4–7). The synthetic fertilizer treatment also had lower yields than some of the compost treatments for beans (years 5–7), carrots (years 6–7), and peppers (4–7). Pairwise comparisons based on Wilcoxon rank-sum tests did not show differences at the significance level of 0.05.

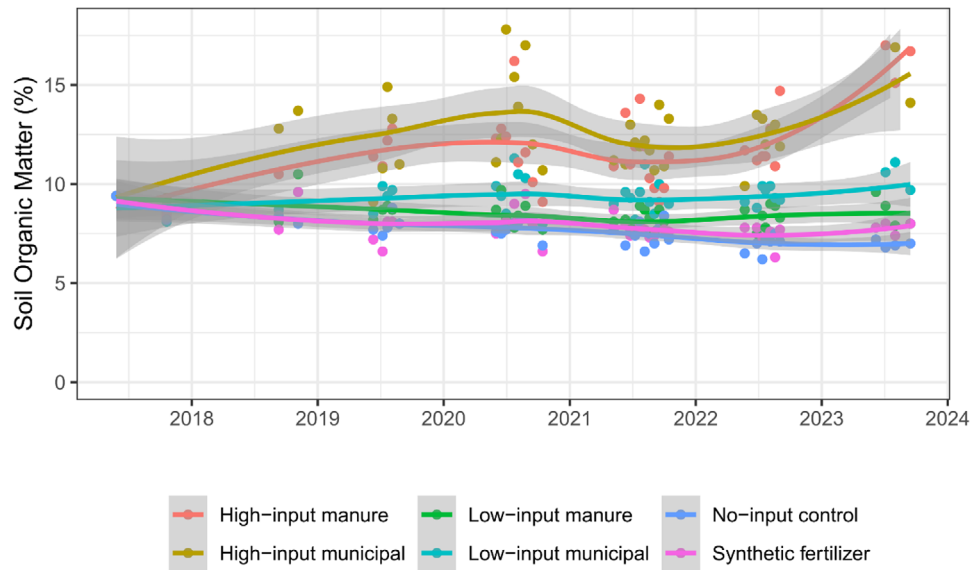


FIGURE 3 Soil organic matter (loss on ignition) from composite samples from each of the six experimental treatments over 7 years. Individual data points represent means of soil samples from individual plots taken at the beginning and end of the growing season in year 1, biweekly composite soil samples collected throughout the growing season during years 2–6, and monthly composite samples during year 7. Lines are smoothed conditional means using the locally estimated scatterplot smoothing (LOESS) method. Shaded areas represent 95% confidence intervals.

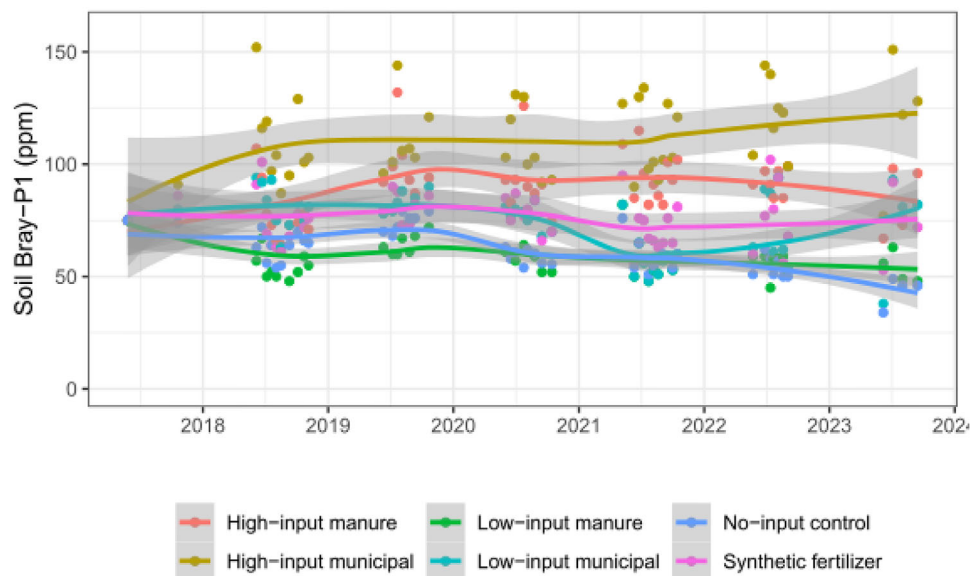


FIGURE 4 Soil plant-available P, measured as Bray P-1 (parts per million [ppm]), from composite samples from each of the six experimental treatments over 7 years. Individual data points represent means of soil samples from individual plots taken at the beginning and end of the growing season in year 1, biweekly composite soil samples collected throughout the growing season during years 2–6, and monthly samples during year 7. Lines are smoothed conditional means using the locally estimated scatterplot smoothing (LOESS) method. Shaded areas represent 95% confidence intervals.

3.6 | Temperature, rainfall, and leachate water flux

Year 5 (2021) was the warmest growing season during the study period (2997 growing degree days), and Year 2 (2018) was the coolest (2379 GDD, Table S8). Seasonal precipita-

tion (June 1–October 15) ranged from 16.6 (2022) to 55.2 cm (2018). Total water inputs (precipitation + irrigation) ranged from 32.5 (2022) to 63.8 cm (2017) (Table 2).

Seasonal leachate water flux values (volume per unit area) were variable across crops, treatments, and years, ranging from 1.2 to 36.8 cm (Table 2; Table S9). However, pairwise

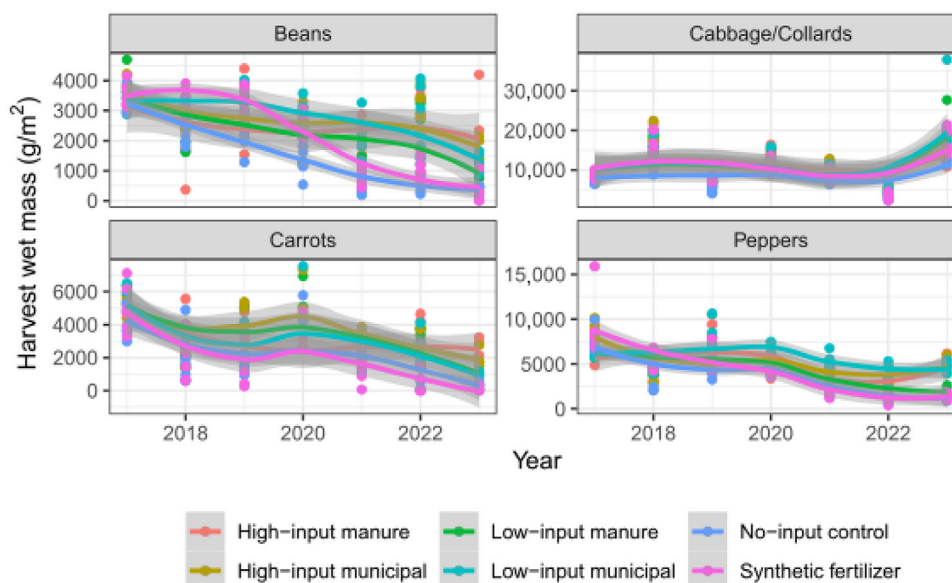


FIGURE 5 Crop yield over the 7-year study. Lines are smoothed conditional means using the locally estimated scatterplot smoothing (LOESS) method, with 95% confidence interval shown.

TABLE 2 Water inputs and leachate losses during the seven growing seasons (June 1–October 15).

	2017	2018	2019	2020	2021	2022	2023
Water inputs (cm)							
Precipitation	49.6	55.2	53.2	34.7	27.5	16.6	44.6
Irrigation	14.2	7.5	4.4	6.8	18.1	15.9	12.1
Total water inputs	63.9	62.7	57.6	41.5	45.6	32.5	56.7
Mean leachate by treatment (cm)							
High-input manure	12.8	28.3	36.8	15.5	18.5	12.8	10.2
Low-input manure	11.2	24.7	31.2	11.9	13.8	4.7	11.7
High-input municipal	9.1	20.1	30.9	9.4	11.1	1.7	11.0
Low-input municipal	9.6	24.3	31.9	14.3	10.5	1.2	7.6
Synthetic fertilizer	10.3	22.6	26.2	7.9	7.6	1.6	8.4
No-input control	12.0	22.5	29.7	10.0	9.7	4.3	9.0

comparisons based on *t*-tests and on Wilcoxon rank-sum tests did not show differences at the significance level of 0.05.

During the two highest-rainfall years (2018 and 2019), leachate accounted for 32%–64% of water inputs. During the lowest-rainfall year (2022), leachate accounted for 39% of water inputs in the high-input manure compost treatment, but only accounted for 4%–14% of water inputs across other treatments (Table 2).

3.7 | Leachate P concentration and flux

Leachate $[\text{PO}_4^{3-}]$ was relatively similar among treatments during the first 3 years of the study, with mean concentrations ranging from 0 to 2 mg P/L across treatments (Figure 6). These values diverged during years 4–7. During 2021 and

2022 (years 5 and 6), which were characterized by low rainfall and low leachate volumes, mean leachate $[\text{PO}_4^{3-}]$ ranged from 10 to 15 mg P/L in the high-input manure compost treatment, and from 6 to 8 mg P/L in the high-input municipal compost treatment (Figure 6). Leachate samples from low-input manure and municipal compost, synthetic fertilizer, and no-input control treatments maintained mean $[\text{PO}_4^{3-}] < 3$ mg P/L.

Weighted regression models showed significant effects of treatment, year, and treatment $\times$ year (Tables S10 and S11). Pairwise comparisons based on *t*-tests (Figure S15) and Wilcoxon rank-sum tests (Figure S16) both showed higher leachate P flux in the high-input manure compost treatment compared to most other treatments each year beginning in year 2. The high-input municipal compost treatment also showed higher leachate P flux compared to the no-input

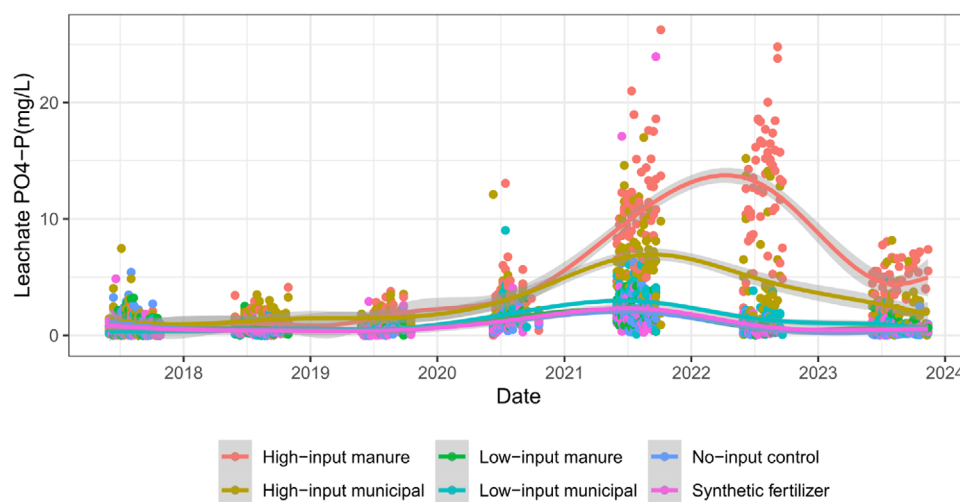


FIGURE 6 Leachate [PO_4^{3-}] (mg P/L) from each of the six experimental treatments. Points represent individual weekly lysimeter samples ($n = 7407$). Lines are smoothed conditional means using the locally estimated scatterplot smoothing (LOESS) method. Shaded areas represent 95% confidence intervals.

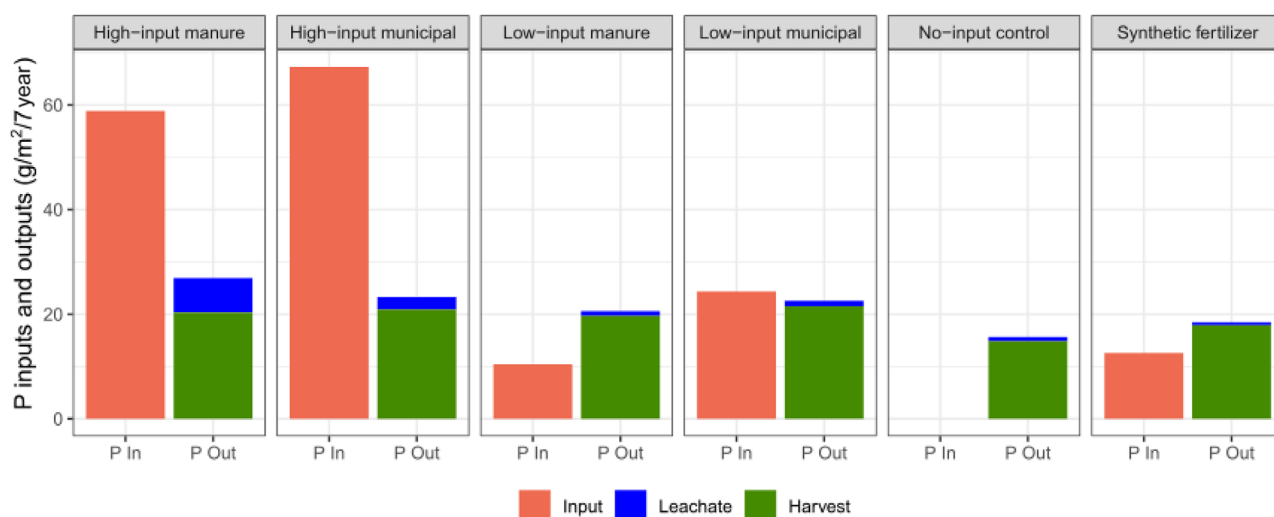


FIGURE 7 A 7-year cumulative P budgets for the six soil amendment treatments in this study. P inputs, shown in red, represent P in compost or synthetic fertilizer added to the garden plots. Phosphorus outputs consist of crop harvest (shown in green) and leachate export (shown in blue).

control treatment (years 2–5 and 7), the synthetic fertilizer treatment (years 2–7), and the low-input municipal compost treatment (years 3, 5, and 7) (Figure S15).

3.8 | P budgets

Across the 7-year study period, cumulative P inputs ranged from 0 to 67.27 g P/m², with similar P input values recorded for both of the high-input compost treatments (Figure 7; Table S12). Cumulative crop P uptake (harvested biomass) ranged from 14.83 to 1.56 g P/m², with similarly high values recorded in all four treatments receiving compost inputs (range 19.66–21.56 g P/m²). Over the 7-year study, the amount of P

in harvested crop biomass in the high-input treatments of manure and municipal compost corresponded to approximately 34% and 31%, respectively, of the amount of total P added as compost. Crop uptake in the low-input manure compost treatment was nearly twice the magnitude of P that was added as compost, and crop uptake in the low-input municipal compost treatment corresponded to 89% of the mass of added P. In the synthetic fertilizer treatment, crop uptake was 42% greater than the mass of added P over 7 years.

The highest P leachate values were observed in the high-input manure compost treatment, with 6.54 g P/m² being exported as leachate over seven growing seasons. Notably, 73% of this P flux occurred during years 5–7. The high-input municipal compost treatment exported 2.39 g P/m² as

leachate over 7 years, and all other treatments had leachate values at or below 1 g/m². The ratio of cumulative harvested P to cumulative leachate P was greatest in the synthetic fertilizer treatment (32.2) and lowest in the high-input manure treatment (3.1).

4 | DISCUSSION

4.1 | Emerging temporal trends

The 7-year time series clearly shows effects that were not present or were subtle earlier in the experiment. After the first 2 years of this study, there was no statistically significant effect of treatment on crop yields (Shrestha et al., 2020), but clear differences in yield among treatments for certain crops are present after 7 years. The lower crop yields in the no-input control treatment may be due to N limitation (Figures S11 and S12), as concentrations of P and K (Figure S13) remained at relatively high levels. However, it is also notable that the synthetic fertilizer treatment eventually led to reduced yields in some crops. It is possible that a higher fraction of the N inputs (added periodically throughout the growing season) was lost through leachate, leading to N limitation. It is also possible that micronutrients supplied by the compost but not the synthetic fertilizer became limiting, or that other properties of the compost (e.g., retaining soil moisture) contributed to differences in yield.

Similarly, during the first 2 years, small (but statistically significant) differences in P leachate were present among treatments (Shrestha et al., 2020). These differences have amplified over time, with pronounced differences during years 5–6 (Table S12). In the high-input manure treatment, 71% of cumulative P-leachate occurred during these 2 years. The elevated leachate P flux in the high-input manure compost treatment is due to a combination of higher leachate PO₄-P concentrations, especially during years 5–7 (Figure 6), and relatively high water leachate fluxes during these years (Table 2; Figure S4).

These results underscore the need for long-term studies that can capture the temporal dynamics inherent in an ecosystem characterized by slowly mineralizing organic matter.

4.2 | Fate of surplus P

Our results show that multi-year inputs of compost at levels that exceed crop P-demand result in increased P storage in soils and, eventually, increased P export as leachate. Similar results have been shown where manure application is used to meet crop N demand in conventional agricultural systems (Eghball, 2007; Toth et al., 2006). However, in our study, the

fate of surplus P was notably different between the two different high-input compost treatments. While both high-input manure compost and high-input municipal compost treatments received a similar mass of P (Figure 7) resulting in surpluses of approximately 38 g P/m²/year, and both had similar soil organic matter content (Figure 3) after 7 years, the municipal compost inputs resulted in soil plant-available P concentrations that were approximately 33% higher than in the high-input manure compost treatment (Figure 4). By contrast, the high-input manure compost treatment exported nearly three times more P through leachate compared to the high-input municipal compost treatment (Figure 7; Table S12), despite maintaining lower soil plant-available P concentrations.

These differences may be partially explained by the rapid mineralization rate of the manure compost (Figure 2) generating more PO₄³⁻ early in the growing season before plant roots were fully developed, resulting in higher losses (van Es et al., 2004). However, the differences between the consistently higher Bray P-1 in the high-input municipal compost treatment and higher leachate [PO₄³⁻] in the high-input manure compost treatment suggest that only a small fraction of the pool of plant-available P is susceptible to leachate, and that this plant-available P is retained in the soil more efficiently in the municipal compost treatment.

The three treatments in which P inputs were targeted toward anticipated crop P demand (low inputs of manure and municipal compost, and synthetic fertilizer) all had low P leachate export (0.56–1.03 g P/m² over 7 years) while maintaining levels of plant-available P that were steady or slowly declining. Notably, the soil plant-available P (Bray-P1) levels were still high relative to the threshold of 25 ppm (Figure 4), above which no additional P inputs are recommended (Rosen et al., 2008). These three treatments were similar in P-input rates to those of an 80-year experiment in Sweden, which documented increased crop yield relative to the no-input control treatment but no buildup of soil P in the top 20 cm of soil (Spohn et al., 2023).

The no-input control treatment in our study exported 0.79 g P/m² as leachate over 7 years (Table S12), with 61% of this P leachate during the first 3 years, indicative of the slowly declining losses from the initial pool of organic matter in the soil. It is notable that both low-input compost treatments have P leachate fluxes similar in magnitude to the no-input control treatment (Figure 7; Table S12), suggesting that most of the leachate export accounted for in those treatments may have been from older organic matter in the soil rather than from compost added during the 7-year experiment. The pool of plant-available P declined by approximately one-third in the no-input control treatment over the 7-year study period, corresponding to net P exports (harvest plus leachate) of 15.6 g/m² over this time (Table S12).

4.3 | Potential for P accumulation and export

The buildup of plant-available P over 7 years observed here is consistent with survey results reported by Small et al. (2019), which found a positive correlation between garden age and soil plant-available P. Notably, the compost input rates used in this experimental study are low relative to P-input rates reported by urban farmers and gardeners for Minneapolis-Saint Paul (Small et al., 2019). The high compost input rates in our experimental study (approximately 10 g P/m²/year; Table S12) are equivalent to the first quartile of reported P input values across urban farms and gardens in Minneapolis-Saint Paul. Median P-input values (30 g P/m²/year) and third quartile values (120 g P/m²/year) would accumulate P at much higher annual rates, presumably leading to higher export of leachate and runoff. In a previous experiment using higher inputs of manure compost and municipal compost from these sources (Small et al., 2018), we documented P leachate levels during a single growing season that were similar to values achieved after 5 years of lower compost inputs in the current study. The experimental results reported here are important because they show that, even at relatively low P input rates, a persistent annual P surplus results in soil P buildup and eventual elevated leachate export.

The relatively few P budgets published for urban agriculture systems, reviewed in van de Vlasakker et al. (2022), show a wide range of annual P balances, from values as high as 182 kg P/ha/year (18 g P/m²/year) in Montreal (Metson & Bennett, 2015) to values near or below zero in Ethiopia (Tadesse et al., 2018) and Sudan (Abdalla et al., 2012). Phosphorus input values in our experimental high compost input treatments are similar to values reported across 25 urban farms and gardens in the Netherlands, which were on average 6-fold higher than estimated crop uptake values (Wielemaker et al., 2019).

Our results may help shed light on the lack of a clear relationship between P inputs and P leachate flux documented across the few published datasets (van de Vlasakker et al., 2022). Different soils have different capacities to retain excess P (based on soil mineralogy, clay content, and pH; Batjes, 2011). When this retention capacity is exceeded, excess P is exported as leachate (Heckrath et al., 1995). Our results show that not only do input rates affect these temporal dynamics, but the source material of compost is an important control of the fate of surplus P, with manure-based compost contributing to higher leachate export.

It is important to acknowledge that, while we measured the export of P from garden soil as leachate at a depth of 30 cm, the ultimate fate of this P may vary depending on site-specific factors. Where gardens have underlying native soil, as in our research garden, this soil is likely to retain much of the leached P (Small, Osborne, et al., 2019). Over longer time scales, soil P can become saturated along hydrologic flowpaths (Sharp-

ley et al., 2013), ultimately contributing to higher P export from terrestrial to aquatic ecosystems. The highly engineered hydrology that characterizes most cities adds a large degree of uncertainty to the capacity for urban watersheds to retain excess P, and the timeline beyond which hydrologic P export would be expected to increase. We note that some urban farms in the Minneapolis-Saint Paul metro area have a shallow layer of compost-enriched soil atop an impervious surface (asphalt or clay), so the resulting leachate may have fewer opportunities for P retention. In a recent spatially explicit urban watershed nutrient model analysis conducted by our group, we showed that watershed P export from compost inputs to urban farms and gardens is highly dependent both on P input rates and on P retention capacity along these hydrologic flowpaths (Small et al., 2023).

4.4 | Optimizing ecosystem services and managing potential tradeoffs

Urban agriculture has the potential to contribute to a variety of ecosystem services, including food security, human health, social inclusion and justice, and economic and environmental sustainability (Orsini et al., 2020). However, as with other ecosystem services provided by urban green spaces, these benefits are often characterized by context dependency and some level of uncertainty (Keeler et al., 2019). Environmental tradeoffs have previously been recognized for urban agriculture, with potential benefits including urban heat island mitigation, stormwater infiltration, and organic waste recycling balanced against risk of nutrient pollution (Rao et al., 2022). Previous work has shown that management differences in urban agriculture settings can affect processes such as water infiltration and nutrient cycling (Cabral et al., 2017).

The results reported here focus specifically on tradeoffs around nutrient management. Different management strategies may optimize various metrics of success, creating the potential for tradeoffs in nutrient recycling. Maintaining high yields is often a primary goal of many commercial urban farmers. We found that all treatments receiving compost inputs (even low inputs) performed similarly well (Figures 5 and 7). The no-input control treatment was, for two of the four crops, the worst performer, with the gap in crop yield growing larger over time.

Another potential metric of sustainability for outdoor urban agriculture is the capacity to receive recycled nutrients. As cities generate more compost from recycling municipal organic waste, finding beneficial uses for this material is a valid goal. In this regard, both high-input compost treatments sequester the largest mass of P that was previously part of the waste stream, making it potentially available for recovery by crops. However, after multiple years of compost addition, P export from leachate was nearly three-fold higher for manure

compost compared to municipal compost, so that the net P sequestration from high-input municipal compost application is greatest.

While the application of recycled nutrients to an urban farm or garden is a component of nutrient recycling, truly recycling these nutrients back into the human food system requires uptake by crops. Therefore, considering the mass of recycled P recovered by crops may be an appropriate metric to consider, although it is a metric that is difficult to directly quantify. All four of the compost treatments had similarly high cumulative yields that were at least partially supplied by recycled P from compost added during the 7-year study period. However, the relatively high sustained yields in the no-compost control treatment suggest that much of the crop nutrient demand may have been supplied from slowly decomposing organic matter that was present at the start of the current experiment.

Minimizing P loss from farms and gardens as leachate or runoff may be a priority, especially in cities in proximity to P-sensitive freshwater ecosystems. Our results indicate that all treatments applying P inputs at or below anticipated crop P demand produce relatively low rates of P leachate, with low compost inputs having only slightly higher rates of P leachate export compared to the no-input control. Just as careful management of lawn P fertilizer has been shown to reduce P export from runoff and leachate (Bierman et al., 2010; Lehman et al., 2009), management of garden P inputs may be important in reducing P export from gardens that could ultimately contribute to eutrophication (Small et al., 2023).

While it may not be possible to optimize every metric of sustainability, our data indicate that tradeoffs are not inevitable. Compost inputs targeted to crop P demand maintain high yields, recycle P from the waste stream back into the human food system, and result in low leachate export.

5 | CONCLUSIONS

Results from our 7-year experimental study show that targeting compost inputs for crop P demand leads to high crop yields, stable soil plant-available P levels, and low P leachate export. However, applying compost based on crop N demand results in a steady buildup of surplus P, which ultimately leads to high leachate export, especially for manure compost. Just as conventional agriculture is increasingly operating under negative P surplus, urban agriculture may need to become more adept at mining existing stocks of P in garden soils. Our results show that intentional P management leads to high yields while minimizing P loss due to leachate. However, excess P inputs ultimately lead to elevated leachate export, highlighting a challenge of nutrient recycling from compost-based urban agriculture. As cities generate larger volumes of compost, finding beneficial uses of this material without contributing to nutrient pollution may become a challenge.

AUTHOR CONTRIBUTIONS

Gaston E. Small: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; writing—original draft; writing—review and editing. **Paliza Shrestha:** Data curation; investigation; visualization; writing—review and editing. **Carolyn Zeiner:** Data curation; investigation; methodology; writing—review and editing. **György Barabás:** Formal analysis; methodology; validation; visualization; writing—original draft; writing—review and editing. **Geneviève Suzanne Metson:** Formal analysis; methodology; validation; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Gaston E. Small  <https://orcid.org/0000-0002-9018-7555>

Carolyn Zeiner  <https://orcid.org/0000-0002-4847-4673>

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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