

## Research Paper

# The sanitation and urban agriculture nexus: urine collection and application as fertilizer in São Paulo, Brazil

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### ABSTRACT

Separately collected urine is an attractive potential fertilizer because of its high nutrient content, low cost, and inherent linkage of urban wastewater management and peri-urban agriculture. Urine from waterless urinals was applied to corn and lettuce plants to examine the impact of urine application rates and frequency on plant growth and soil parameters. In both corn and lettuce experiments, urine application significantly ( $p < 0.05$ ) increased growth and leaf production relative to control plants. More frequent applications led to lower soil cation exchange capacities for corn and higher soil nitrogen content for both crops. Based on preliminary implementation calculations, waterless urinals at the University of São Paulo (USP), School of Arts, Sciences, and Humanities campus could lead to over 1,500 m<sup>3</sup> of water saved and 360 m<sup>3</sup> of urine produced on an annual basis. These experiments and modeling results are discussed in the context of scaling up urban urine collection, transport, and fertilization in São Paulo, Brazil.

**Key words** | fertilizer, nexus, source separation, urine

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### INTRODUCTION

Urine has emerged as a promising potential fertilizer because it is ubiquitous and inexpensive. Historically, farmers have mostly used their urine to grow crops for their own consumption (Bond *et al.* 2013). Recently, higher-density pilot systems have been constructed to collect and apply urine to fields (Berndtson 2006; Rossi *et al.* 2009). Urine is an attractive fertilizer because it has a high nutrient content but low pathogen content (Bischel *et al.* 2015). Urine contains 90% of the nitrogen, 65% of the phosphorus, and 80% of the potassium that humans excrete (Rose *et al.* 2015). Although the nutrients present in urine are valuable (Etter *et al.* 2011), its current categorization as a waste stream makes it inexpensive. Several studies have examined the effect of urine on plant growth (Guzha *et al.* 2005; Pradhan *et al.* 2007), but most have not considered the engineered systems for collecting and transporting urine as fertilizer.

Capturing urine separately from feces requires alternative sanitation systems like waterless urinals and source-

separating toilets, which can be implemented in sewerred (NoMix) or unsewered (urine-diverting dry toilet) contexts. Once collected, urine can be transported by either separate pipes or by truck. Both retrofitting separate piping and trucking urine, which is 96% water (Drangert 1998), can be expensive. Depending on population density and proximity to farmlands or urban gardens, transport may be financially feasible. Collection and transport challenges, as well as modern population shifts like the majority of people living in cities (UN 2015), have created a new question: can we engineer an efficient collection and conveyance system for urine fertilization?

The present study is one of the first to connect urine fertilizer efficacy to engineered systems for urine collection and transport in Brazil. Although an investigation of urine-fertilized plants has been performed in a peri-urban community (Botto & dos Santos 2013), adding data and models from

an urban setting can help answer logistical questions associated with larger scale, more centralized systems. With over 21 million residents (UN 2015), São Paulo Metropolitan Region is one of the six most populous megacities in the world. Engineering large-scale urine collection systems intensifies some of the challenges of urine management, such as ammonia volatilization and phosphate precipitation. Urine contains fewer pathogens than feces, but may need to be disinfected before application. While storage is a common disinfection option due to an increase in pH that can deactivate pathogens (WHO 2006), immediate transport eases management by reducing volatilization.

In comparison to urine's nutrient composition and its effects on crops, appropriate application rates remain an open question. Our comparison of extremely different application regimes is a step towards determining optimal application rates and frequencies. Measuring soil parameters along with crop characteristics is also a novel part of this study and gives insight into long-term effects beyond one growing season and harvest (Lepsch et al. 1994). Eventually, a consensus from studies like the present one can be used to prescribe application rates, application frequencies, and soil effects for urine fertilization.

The goal of this study was to evaluate the potential use of source-separated urine as fertilizer in São Paulo, Brazil. São Paulo is an ideal city to test and potentially implement urine collection because of its high population and urine production densities; its proximity to agricultural lands (Sano et al. 2009); and its current drought and aging water infrastructure (Reuters 2015), which may incentivize low water-use alternatives like source separation. Our specific objectives were to determine the effect of varying urine application rates and frequencies on corn growth, lettuce growth, and soil parameters. We then used these results and experiences to model logistics and potential benefits of collecting and applying urine as fertilizer.

## METHODS

### Description of case study

A pilot-scale study of urine collection and application as fertilizer was conducted in Academic Building A3 (School of

Arts, Sciences, and Humanities) on the campus of the University of São Paulo, in São Paulo, Brazil (23°29'0"S, 46°30'8"W). Annual average temperature was 19°C and annual average rainfall was 1,680 mm. There are six male restrooms in the building and each has three urinals (18 total). In one of them we replaced one conventional, watered ceramic urinal with a fiberglass waterless urinal (Uridan™; Haderslev, Denmark). The waterless urinal was connected using PVC pipe to a storage tank, ensuring the entire system was airtight to avoid ammonia volatilization. Between 200 and 300 students, faculty, and staff use the building each day. About 1.6 L of urine was collected each day and added to a larger storage tank. Urine remained in the storage tank for at most 1 week before application. Although urine composition was not determined, urine has been well documented to contain high concentrations of potassium, ammonium, and phosphorus (Udert et al. 2006). No solid precipitates were observed in the urine collection or storage containers. Plant nursery experiments were conducted to determine the effect of urine fertilization on soil characteristics and the response of two species: *Lactuca sativa* L. and *Zea mays* L. The choice of these species was due to their robustness, fast growth, and their high rates of consumption in Brazil (Caldarelli & Bacchi 2012; Sala & da Costa 2012). Lettuce and corn were also chosen to contrast the effect of urine fertilization on plants with high (corn: 160 kg N/ha/yr) (Gensch et al. 2011) and low (lettuce: 45 kg N/ha/yr) nitrogen requirements (Gensch et al. 2011).

### Description of treatments

We established two treatments for corn and three treatments for lettuce, each receiving different urine dosages. We also established one control treatment for each species (non-fertilized, only irrigated with tap water). Regardless of urine dose, all treatments were watered manually with tap water (corn: 400 mL/pot, 3 times/wk; lettuce: 180 mL/pot, 3 times/wk). Experiments were conducted in 8 L (lettuce) and 10 L (corn) pots filled with topsoil rich in organic matter, typical of soil in the São Paulo region (Lepsch et al. 1994). The corn and lettuce trials included ten replicate pots, each with three corn seeds or six lettuce seeds, for each treatment and control. Urine dosages were based on the

nitrogen requirement of each species, the nitrogen content of urine, and previous studies evaluating urine for crop cultivation (Table 1). Urine was applied directly to holes made in the soil with a plastic watering can and urine application was followed by watering to avoid soil salinization and toxicity effects on the plants (Gensch *et al.* 2011).

### Parameters measured

Number of leaves and live plants were recorded periodically throughout the growth period. The study lasted 167 and 98 days for corn and lettuce, respectively. At the end of the growth period, plant parameters were measured. Based on previous plant growth experiments (Guadarrama *et al.* 2002; Morgan 2005; Galvão *et al.* 2009), we chose to measure root weight, leaf area, and shoot dry weight for corn plants, as well as root length and shoot fresh weight for lettuce plants. Root weight and length can indicate the hydric deficit of the plant; leaf area is related to light interception and photosynthetic capacity; and shoot weight is related to the nutrient uptake efficiency of the plant (Galvão *et al.* 2009). Shoot dry weight was determined by drying plants for 5–6 days at 55–75 °C until they reached a constant weight. Leaf area was measured with a leaf area meter (LI-COR, Omaha, Nebraska).

Composite soil samples were taken from 0 to 15 cm depth in each pot. Physicochemical soil parameters were measured, including organic matter content, macronutrient content

(potassium, phosphorus, and nitrogen as total nitrogen, ammonia, and nitrate), micronutrient content (boron, zinc, manganese, iron, and copper), sulfur content, magnesium content, calcium content, pH, electrical conductivity, and cation exchange capacity (CEC). Organic matter was measured with the dichromate colorimetric method. Ion chromatography was used to measure  $K^+$ ,  $Ca^{2+}$ ,  $Mg^{2+}$ , and  $HPO_4^{2-}$ . Boron and sulfur were extracted with microwave heating and 0.1 M  $Ca(H_2PO_4)_2$  solution, respectively. Total nitrogen and ammonium were measured by standard Kjeldahl methods; nitrate was measured with MgO/Raney catalysts. Fe, Cu, Mn, and Zn were determined using diethylenetriaminepentaacetic acid (DTPA) solution at pH 7.3.

Soil pH and electrical conductivity were measured throughout the experiment to monitor salinization and acidification, both of which can inhibit plant growth (Munns 1993; Munns & Sharp 1993). Both parameters were measured with a pH/electrical conductivity probe (Quimis), pH was determined in 0.01 M  $CaCl_2$  solution; electrical conductivity was determined in deionized water.

### Statistical analysis

For each treatment and plant growth parameter (area, mass, leaf area, length), data from all 30 (corn) or 60 (lettuce) plants were subjected to analysis of variance and paired t-tests using Minitab 16 statistical software. Significant differences are noted throughout the ‘Results and discussion’ section.

**Table 1** | Application rates for each plant species and type of treatment

Treatment/ Species	Corn	Lettuce
A	25,000 L/ha (125 mL/pot) of neat urine applied weekly for 8 weeks (total: 200,000 L urine/ha) <sup>a</sup>	4,000 L/ha (16 mL/pot) of neat urine applied every 15 days (total: 12,000 L urine/ha) <sup>b</sup>
B	10,800 L/ha (54 mL/pot) of neat urine applied at one time (35 days after seeding; total: 10,800 L urine/ha) <sup>c</sup>	75,000 L/ha (400 mL/pot) of neat urine diluted and applied as follows: 1st month: twice per week, 3:1 dilution (water:urine). 2nd month: twice per week, 5:1 dilution. 3rd month: once per week, 5:1 dilution. (Total: 1,500,000 L urine/ha) <sup>a</sup>
C	No urine (control)	20,000 L/ha (51 mL/pot) of neat urine, one application 48 days after seeding (total: 20,000 L urine/ha) <sup>d</sup>
D	–	No urine (control)

<sup>a</sup>Morgan (2005).

<sup>b</sup>AC (2005).

<sup>c</sup>Coelho *et al.* (2011).

<sup>d</sup>Guadarrama *et al.* (2002).

## Implementation calculations

Water savings, urine produced, and farms fertilized were calculated for a potential urine collection and fertilization system at the University of São Paulo. The volume of water saved ( $V_w$ , m<sup>3</sup> water/yr) was calculated according to Equation (1):

$$V_w = F * n * \frac{3.78 \text{ L/gal}}{1000 \text{ L/m}^3} \quad (1)$$

where  $F$  is annual water savings for reduction in 1 L/flush for conventional urinals (4,600 gal/yr/urinal, [WaterSense Labeled Urinals 2013](#)) and  $n$  is the number of urinals on USP campus (89). The volume of urine produced ( $V_u$ , m<sup>3</sup> water/yr) was calculated according to Equation (2):

$$V_u = \frac{P * U * t}{1000 \text{ L/m}^3} * 365.25 \frac{\text{d}}{\text{yr}} \quad (2)$$

where  $P$  is university male population (approximately 2,930 at School of Arts, Sciences, and Humanities campus),  $U$  is an average urine production rate of 1.4 L/person/day ([Rose et al. 2015](#)), and  $t$  is an assumed proportion of time spent on campus (40 hr/week = 0.24). Annual fertilized land areas for each crop ( $A$ , ha/yr) were calculated using Equation (3):

$$A = \frac{V_u}{R} \quad (3)$$

where  $V_u$  was volume of urine produced (m<sup>3</sup> urine/yr) and  $R$  was the fertilization rate for the treatment with highest plant growth parameters for each crop (m<sup>3</sup> urine/ha).

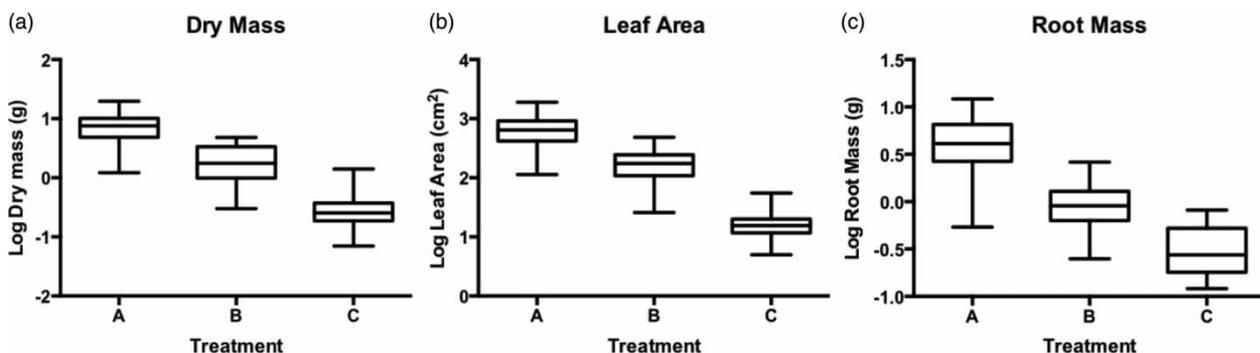
## RESULTS AND DISCUSSION

In both corn and lettuce experiments, urine application significantly ( $p < 0.05$ ) increased growth and leaf production relative to the control treatments.

### Corn plant growth

Corn plant shoot dry weight, leaf area, and root weight were highest in treatment A, lowest in treatment C (control), and intermediate in treatment B ([Figure 1](#)). All three metrics were significantly higher ( $p < 0.05$ ) for treatment A vs. treatment B, as well as treatment B vs. treatment C. Similar trends were observed for the number of cobs at cultivation: 17 cobs (ears of corn) in treatment A plants, two cobs in treatment B plants, and none in treatment C plants. Plant height and number of leaves were also highest in treatment A, followed by treatment B and the control. Corn belonging to the control took more time to grow in height and number of leaves than urine-fertilized plants. Based on these results, fertilization with urine stimulated corn plant growth relative to the negative control. From these results and previous correlations between shoot dry weight and nutrient uptake efficiency ([Mengel & Barber 1974](#)), we concluded that urine fertilization led to not only more available soil nitrogen, but higher uptake efficiency by corn plants.

Based on leaf color intensity, control corn plants showed symptoms of phosphorus and nitrogen deficiency, while the leaves of treatment B plants presented symptoms of nitrogen deficiency ([Ferreira et al. 2001](#)). Treatment A plants had dark green leaves and no signs of nutrient



**Figure 1** | Corn (a) dry mass, (b) leaf area, and (c) root mass at end of the growth period.

deficiency. None of the plants in the treatments A, B, and C reached physiological maturity. However, all plants belonging to treatment A were in the reproductive stage, most of the plants of treatment B were in this stage, and only two control plants were in this stage.

Comparing treatments A and B gave further insight into optimal urine application schemes. As treatment A had more frequent urine dosages and more urine applied in each dose, it is not possible to separate the effects of urine volume and frequency in this study. Applying fertilizer more frequently could increase plant yield because of a more regular supply of nutrients; however, frequent fertilization can also damage plants through an over-accumulation of nitrate in soils (Roth & Fox 1990). The higher plant growth metrics observed in treatment A could also be the result of more urine applied in treatment A than treatment B.

### Corn soil

Physicochemical soil parameters can be found in Table 2. Soil pH decreased for all treatments during the growth period. This acidification was expected due to hydrolysis of urea to bacterial  $\text{NH}_4^+$  (Udert *et al.* 2006), which can exchange with protons in plant roots (Bouman *et al.* 1995). Soil fertilized only once with urine (treatment B) had a much higher CEC than control soil and soil regularly fertilized with urine. CEC is a relevant soil parameter because it has been demonstrated

to increase yield due to more adsorption sites available for concentrating macronutrients and micronutrients near plant roots (Liang *et al.* 2006). With weekly applications, changes in CEC due to urine application and corn growth may have equilibrated; with a one-time application later in the experiment, urine fertilization had a separate and additional effect on CEC. In implementation, waiting 5 weeks to fertilize corn may lead to higher soil CEC values, which can increase corn yield. This same phenomenon may explain how soil magnesium concentrations were highest for one-time urine fertilization although much more total urine was added in the weekly regime.

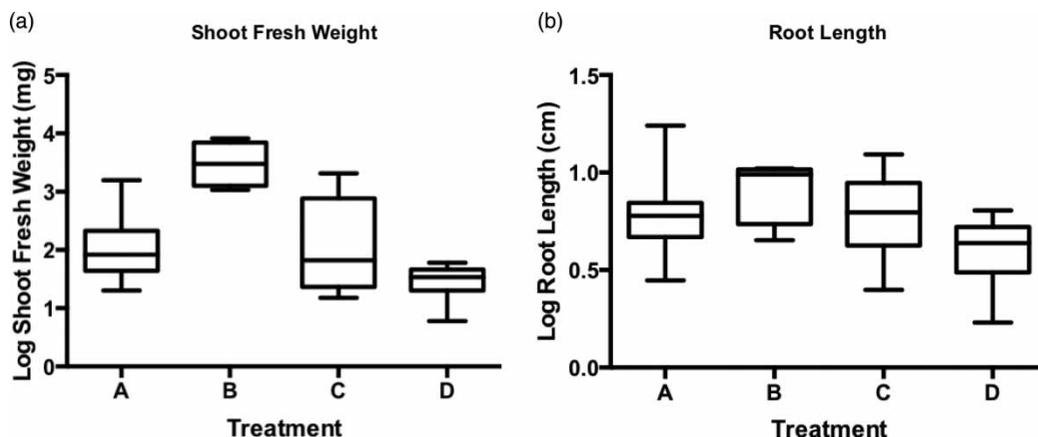
Fertilization frequency also affected soil potassium concentrations. While both one-time urine fertilization and the control groups showed a decrease in soil  $\text{K}^+$  content, weekly urine application replenished  $\text{K}^+$  loss and led to a slight increase over the course of the experiment. Similarly, soil electrical conductivity was highest and pH lowest for weekly urine application (treatment A: 5.2 mS/cm, B: 0.9 mS/cm, control: 0.76 mS/cm). These results could also be explained by the larger total volume of urine applied.

### Lettuce plants

In lettuce experiments, treatment B plants (highest urine dosage) exhibited the highest values of shoot fresh weight and root length (Figure 2). The control group had the

**Table 2** | Soil physicochemical properties before and after the corn was fertilized with urine

Parameter	Before treatment			After treatment		
	A	B	C	A: 25,000 L/ha neat urine	B: 10,800 L/ha diluted urine	C: control (no urine)
pH	6.7	6.8	6.9	5.8	6	6.1
Organic matter (g dm <sup>-3</sup> )	77	78	94	100	102	106
Mg (mmol dm <sup>-3</sup> )	30	26	28	26	45	30
S (mg/dm <sup>-3</sup> )	191	187	247	21	19	24
CEC (mmol/dm <sup>-3</sup> )	125	114	118	134.4	153.5	137.5
P (mg dm <sup>-3</sup> )	94	105	96	171	129	177
K (mmol dm <sup>-3</sup> )	19	18	17	19	14.5	14.5
Ca (mmol dm <sup>-3</sup> )	61	56	60	75	79	78
Mg (mmol dm <sup>-3</sup> )	30	26	28	26	45	30
Al	0	0	0	0	0	0
Potential acidity (mmol dm <sup>-3</sup> )	16	14	13	15	15	15



**Figure 2** | Lettuce (a) shoot fresh weight and (b) root length at end of the growth period.

lowest values, and fresh shoot weight and root length were proportional to the amount of urine applied to the substrate. This trend indicates the positive effect of urine as a fertilizer for lettuce. Higher shoot fresh weight values indicate that urine-fertilized plants had higher water retention capacity and higher nutrient availability in the substrate (Buso & Bliss 1988). Higher root length values indicate better plant growth and better absorption of nutrients and water (Buso & Bliss 1988). Both shoot fresh weight and root length were significantly different for all four treatments ( $p < 0.05$ ).

Although lettuce plants in treatment B had the most leaves, they also showed the highest mortality. Compared to treatment B, treatments A and C had lower urine application rates, growth metrics, and mortality rates. From these results we concluded that there is some critical value of urine application (between 20,000 and 1,500,000 L/ha) above which mortality outweighs lettuce growth benefits. In future work this maximum application rate could be more accurately estimated. Based on a comparison of treatments A and C, the more frequent application of treatment A was outweighed by the higher total application rate in treatment C. From this result we concluded that frequency is less significant than total volume of urine applied for urine fertilizer efficacy on lettuce plants.

### Lettuce soil

Plants fertilized with the largest total urine volume had the highest micronutrient (B, Cu, Mn, Zn) content. Boron has been detected in urine at concentrations less than 0.1 mg/L

(Meacham *et al.* 1995), but its absorption can be reduced by nitrogen (Petridis *et al.* 2013). Thus, the trends discussed for lettuce growth relative to macronutrients in urine may also be related to urine-derived boron.

The order of treatments was the same for nitrogen content in soil and urine application rate. This trend was expected given the high nitrogen concentration in urine. The exception was treatment A having a higher nitrogen content than C, although the latter received more urine. More frequent urine application may have led to more uptake of nitrogen as ammonium by soil in treatment A. More ammonia might volatilize in the one-time urine application in treatment C, which would be replenished in the more frequent applications of treatment A.

Soil pH for the control treatment increased slightly from 6.5 to 6.8 over the course of the experiment. All urine treatments showed less of an increase than the control; in particular, treatment B had a much more acidic pH and the highest potential acidity (Table 3). The low pH of fresh urine (~6 (Udert *et al.* 2006)) and exchange of urine cations for protons may have led to slight soil acidification (Bouman *et al.* 1995). This conclusion was corroborated by the decrease in exchangeable  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  for treatment B, which commonly decrease in more acidic soils (Bouman *et al.* 1995). Soil acidification and lower divalent cation concentrations support our theory of a critical urine application, above which, deleterious effects outweigh benefits. In addition, plants in treatments A and B showed yellow precipitate and fungi in the soil upper layer. Both of these phenomena could indicate over-fertilization with urine.

**Table 3** | Soil physicochemical properties before and after lettuce was fertilized with urine

Parameter	Before treatment	After treatment			
		A: 12,000 L/ha neat urine	B: 1,500,000 L/ha diluted urine	C: 20,000 L/ha neat urine	D: control (no urine)
pH	6.5	6.5	5.6	6.7	6.8
Organic matter (g dm <sup>-3</sup> )	97	106	108	106	114
B (mg dm <sup>-3</sup> )	–	0.73	1.27	0.61	0.72
Cu (mg dm <sup>-3</sup> )	–	6.5	7.8	5.9	4.6
Fe (mg dm <sup>-3</sup> )	–	47	53	63	52
Mn (mg dm <sup>-3</sup> )	–	1	9	2	2
Zn (mg dm <sup>-3</sup> )	–	2.6	3	2.6	2.1
S (mg/dm <sup>-3</sup> )	93	11	40	13	23
CEC (mmol/dm <sup>-3</sup> )	141.3	143	133	137	122
P (mg dm <sup>-3</sup> )	78	55	68	54	49
K (mmol dm <sup>-3</sup> )	0.11	0.055	0.065	0.049	0.039
Total N (mg kg <sup>-1</sup> )	4,200	2,320	3,480	1,930	1,540
N (NH <sub>4</sub> <sup>+</sup> ) (mg/kg <sup>-1</sup> )	4,500	–	–	–	–
N (NO <sub>3</sub> <sup>-</sup> ) (mg/kg <sup>-1</sup> )	2,300	–	–	–	–
Ca (mmol dm <sup>-3</sup> )	86	95	73	92	83
Mg (mmol dm <sup>-3</sup> )	31	27	22	23	21
Potential acidity (mmol dm <sup>-3</sup> )	13	13	27	14	13

### Comparing corn and lettuce

Because corn and lettuce have drastically different nitrogen demands (160 and 45 kg/ha/yr, respectively (Gensch *et al.* 2011)) and nitrogen is the main component of urine, the results of urine fertilization on corn and lettuce growth can potentially be generalized. Other crops with low nitrogen demands include beans, peas, and herbs; tomato, spinach, and eggplants have high nitrogen demands (Cook and Sanders 1991; Gensch *et al.* 2011). Although frequency and volume of urine application could not be separated in corn experiments, frequency was determined to be less significant than volume for lettuce growth. The proposed critical value of urine application above which lettuce mortality outweighs the benefits of urine fertilization either does not exist for corn or was above the highest volume tested (200,000 L/ha).

The effect of fertilization frequency on soil parameters can be compared between corn and lettuce experiments. In lettuce experiments, regular urine application led to

higher nitrogen content in soil; in contrast, corn soils fertilized regularly with urine had lower CEC values than those fertilized once. Both of these phenomena may be related to differences in nitrogen demand. As lettuce has a low nitrogen demand, surplus ammonia from regular urine application would lead to higher soil nitrogen concentrations. Corn plants, which have a high nitrogen demand, are more likely to exchange more cations with surrounding soil and reach a rapid equilibrium relative to the week between urine additions. The investigation of corn and lettuce plants in this study forms a basis for further work with other crops with similar nitrogen demands.

### Comparing urine to synthetic fertilizers

Based on the current underutilization of synthetic nitrogen fertilizers in Brazil by smallholder farmers (FAO 2004), we chose to compare urine application to only irrigation, a practical and economical alternative to urine fertilization for these farmers. The anticipated users of collected urine as fertilizer are not

currently using synthetic fertilizers; in most cases, they are not currently using any fertilizer. Only 38% of farms are currently using lime or fertilizers (FAO 2004). In future work, urine fertilization on common crops in Brazil (like rice, potatoes, sugarcane, and wheat) (FAO 2004) will be compared to synthetic fertilizers. Since our results match those in the literature comparing urine and untreated soils, we expect future results to match those of previous studies comparing urine and synthetic fertilizers. In one study, more corn plants, heavier cobs, and higher kernel weights were observed in soil that received 200,000 L/ha of urine compared to untreated soils and soils with commercial fertilizers (Morgan 2005). Similarly, plants in our treatment A (200,000 L/ha) showed higher number of ears than untreated soils. In another study, urine was compared to synthetic fertilizers with okra plants (Akpan-Idiok *et al.* 2012). The application of 15,000 L/ha and 20,000 L/ha of urine produced plants significantly taller than plants treated with NPK 15:15:15 fertilizer.

Of the farms that are using fertilizer, the relevant comparisons are urea, ammonium phosphate, and potassium chloride (FAO 2004). Both ammonium phosphate and urea have been demonstrated to increase soil acidity, which leads to a decrease in exchangeable  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  (Bouman *et al.* 1995). This phenomenon was observed in our corn treatment with the highest urine volume, but not for more mild treatments. Urine does not have the same acidifying effect on soil as synthetic fertilizers. Urine has also been documented as a slow-release fertilizer, which leads to lower levels of nutrient runoff and eutrophication than when synthetic mineral fertilizers are applied (Gutser *et al.* 2005). As demonstrated by our soil results, urine replenishes both macronutrients and micronutrients in soil. Thus, urine fertilization may address the negative fertilizer balance for many smallholder farmers in Brazil, in which the quantities of nutrients removed by harvest and runoff are greater than the quantities of nutrients added by fertilizer (FAO 2004).

## Implementation

The results from this pilot study are useful for considering the logistics and challenges of implementing separate urine collection and application as fertilizer at larger scales. As São Paulo municipality requires that public buildings implement water saving measures (São Paulo 2005) and

the University of São Paulo is a public university, the university campus provides an ideal setting for a pilot and/or demonstration scale urine collection system and other water-saving initiatives such as greywater collection, treatment and reuse (Chrispim & Nolasco 2017). If waterless urinals were implemented at the campus level, we would expect 1,550 m<sup>3</sup> of water saved annually. These calculations are only for the 89 urinals on the USP School of Arts, Sciences, and Humanities campus; scaling to all USP campuses (over 70,000 students and staff) and installing NoMix toilets that separate feces and urine would increase savings. In the present pilot study with one waterless urinal, very little additional maintenance was required – cleaning and specific odour blocking fluid (e.g. Urilock®) is recommended to be replaced after 7,000 uses. At larger scales, one benefit of public restrooms is that maintenance can be managed by custodial staff (Larsen & Lienert 2007). User acceptance of waterless urinals and source-separating flush toilets will likely play a major role in scaling up urine collection. In our study, students, faculty, and staff alike found the waterless urinal novel and were very willing to use it. A larger sample size of users will yield more robust results. Previous studies have shown that 90% of people approve of source-separating toilets (Larsen & Lienert 2007). In future work, a citywide business model for São Paulo will be explored, including toilet types, water savings, urine and urine-derived products, and potential customers.

There are several steps between urine collection at the toilet and its application as a fertilizer, all of which raise new questions at large scales. If all 89 urinals on the University of São Paulo campus were waterless, 360 m<sup>3</sup> of urine would be collected in a year. This volume is enough to fertilize 15 hectares of corn or 18 hectares of lettuce annually (using corn treatment level A and lettuce treatment level C). Urine volume collected and land area fertilized would increase significantly if the system were adopted at all USP campuses. Collecting urine from different buildings requires pipes and/or trucks to convey urine from the point of excretion to the point of fertilization. A preliminary system might use pipes to convey urine to one central place on campus, where it would then be distributed around the campus for landscape gardening and crop production. Alternatively, urine collected on the campus could be trucked to organic urban gardens less than 20 km away or farther away

to peri-urban farmers. We expect that applying urine as fertilizer as close as possible to the point of collection will increase financial feasibility. Future work includes the logistics and costs of bottling the urine and transporting it to customers. The fate of organic contaminants and pathogens during urine collection has recently been explored in separately collected urine in Durban, South Africa (Bischel *et al.* 2015); future work on monitoring contaminants in soils during pot trials could inform urine treatment before application as a fertilizer. Notable pharmaceuticals include sulfamethoxazole and trimethoprim, which were detected at ppm levels in more than 80% of samples; polyoma virus, *Aeromonas* spp., and *Clostridium perfringens* were detected in more than 70% of samples (Bischel *et al.* 2015).

Public acceptance of urine as fertilizer among farmers and crop consumers will also play a key role in implementation of urine collection and fertilization. A case study in Switzerland showed that 71% of people would buy crops fertilized with urine (Larsen & Lienert 2007). A future goal is to evaluate the feasibility of creating a scalable market by collecting and using urine as a fertilizer at a large scale.

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## CONCLUSIONS

The objective of this study was to determine the effect of urine application on corn and lettuce plant growth. Higher urine application rates led to larger and more numerous corn and lettuce plants, as well as higher soil nitrogen concentrations. Micronutrients like boron also increased with urine application rate, which proved relevant for lettuce. More frequent applications led to lower soil CECs for corn and higher soil nitrogen content for corn and lettuce. Overall, urine application was demonstrated to lead to improved plant and soil metrics.

We extended our results to consider the effects of collecting urine across the University of São Paulo campus and applying it as fertilizer on campus, urban gardens, and peri-urban farmlands. This preliminary study with one waterless urinal provided the basis for calculations at larger scales. Collecting and applying urine as fertilizer could decrease water consumption on the campus and increase access to fertilizers. Water savings are particularly relevant to the São Paulo case study because of recent

droughts and water scarcity. In future work, we will examine the logistical questions concerning scaling urine collection, transport, and application as fertilizer.

In addition to improving plant growth, using urine as a fertilizer can potentially make an impact on grand challenges such as access to sanitation and fertilizer, both of which lie at the agriculture, water, and food nexus. These auxiliary benefits are particularly relevant to Brazil, where only 18% of urban sewage is treated (IBGE 2011) and only 38% of farms use commercial fertilizers (FAO 2004). As urine is ubiquitous and low-cost, safely collecting and using urine as fertilizer can increase the number of people with access to effective fertilizers. In areas with low sanitation coverage, creating demand for urine can increase the number of toilets because they are needed to safely capture urine. These issues are especially pressing in urban areas with high population density, in which 84% of Brazilians live (UN 2015; Cardoso *et al.* 2017). Studies confirming the efficacy of urine as a fertilizer are vital first steps toward implementation of urine collection, which has large potential implications for sanitation and fertilizer access.

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