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Putting the P(ee) in perennial agriculture: Reflections on a workplace urine nutrient reclamation project

SPECIAL ISSUE
Community-Based Circular Food Systems
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Madeline DuBois [a]* and Laura van der Pol [b]
The Land Institute

Tatiana Schreiber [c]
Rich Earth Institute

Aubrey Streit Krug [d] and Timothy Crews [e]
The Land Institute

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Abstract
Phosphorus (P) is a finite resource essential for food production currently lost from fields at an unsustainable rate via runoff and crop harvests. These losses could be addressed by pairing perennial crops, which reduce runoff with their deep roots that stabilize the soil, with recovering nutrients from human excreta. Urine contains the majority of P and other nutrients that humans excrete and therefore has been the focus of recent nutrient reclamation efforts. Urine fertilizer has yet to be explored for perennials, however, and understanding the biophysical effects of urine fertilizer on soil nutrients and biomass in perennial crops could inform the design of a more circular food system. To that end, we started the first known workplace urine nutrient reclamation project in the state of Kansas, U.S., to test the feasibility of supplying available soil P from urine to alfalfa (*Medicago sativa*), a perennial legume forage crop. After one growing season, urine fertilizer had no effect on aboveground biomass but did increase

[a] * *Corresponding author:* Madeline DuBois, Soil Ecology Lab Manager, The Land Institute; 2440 East Water Well Road; Salina, KS 67401 USA; dubois@landinstitute.org; https://orcid.org/0009-0004-5860-3813

[b] Laura van der Pol, Lead Soil Ecologist, The Land Institute; lvanderpol@landinstitute.org; https://orcid.org/0000-0002-9430-5985

[c] Tatiana Schreiber, Social Research Director, Rich Earth Institute; 355 Old Ferry Road; Brattleboro, VT 05301 USA; tatiana@richearthinstitute.org; https://orcid.org/0000-0002-1997-2390

[d] Aubrey Streit Krug, Director of the Perennial Cultures Lab, The Land Institute; streitkrug@landinstitute.org; https://orcid.org/0000-0002-8378-4423

[e] Timothy Crews, Chief Scientist and International Program Director, The Land Institute; crews@landinstitute.org; https://orcid.org/0000-0003-4764-341X

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available soil P which otherwise decreased in the control treatments. Urine also increased soil nitrate and sodium compared to the water-only controls. The field study was coupled with a survey of staff members who participated in urine collection to identify opportunities and potential barriers to urine diversion in the U.S. The survey revealed a lack of awareness of both unsustainable P management and urine recovery as a potential solution, underscoring the need for increased education. Regulatory challenges faced in the second field season also highlighted the need for policy that explicitly defines urine separately from wastewater in the U.S. We hope that results from this project will make it more feasible to conduct additional studies and circular food system community-based projects on a larger scale going forward.

Keywords
nutrient circularity, agroecology, circular economy, community-based research, alfalfa (*Medicago sativa*), food systems, phosphorus, urine

Introduction

Phosphorus (P) is the rock-derived nutrient with the lowest natural abundance in the earth's lithosphere relative to biological demands, and mineable resources are being depleted (Cordell et al., 2009; Vitousek et al., 2010). As a result, P supply could limit future agricultural production. P lost from fields unintentionally via erosion and intentionally via harvest ultimately accumulates in water bodies and landfills in forms inaccessible to soil, driving the need to continuously replace the P removed. Both types of losses could be reduced, however, by pairing perennial crops whose deep roots reduce erosion and runoff (Crews & Brookes, 2014; Culman et al., 2013; Huddell et al., 2023; Jungers et al., 2019) with the practice of reclaiming nutrients from excreta. Applying excreta to crop fields was common in many societies historically, but the practice has been mostly abandoned with our increased reliance on fossil fuel energy and with changes to infrastructure and culture (Kawa et al., 2019). Interest in revisiting this practice has grown, however, with a focus on urine due to its high nutrient content and low risk of disease propagation (Ashley et al., 2011; Kawa et al., 2019; Rose et al., 2015). Studies have shown that urine contributes roughly 79% of the nitrogen (N), 47% of the P, and 71% of the potassium (K) but makes up less than 1% of the volume of municipal wastewater, making urine source separation an attractive option to reduce energy consumption, save water, and conserve finite nutrient reserves (Larsen et al., 2013).

Previous studies on human urine fertilizers have demonstrated their efficacy in increasing biomass production in maize (Andersson, 2015; Kassa et al., 2018), ryegrass (Bonvin et al., 2015; Martin et al., 2021) and lettuce (Chrispim et al., 2017) relative to control plants and even relative to plants amended with commercial fertilizer (Antonini et al., 2012). Experiments have also explored urine-derived P integration into the soil. P fertilizer often becomes quickly unavailable to plants as it adsorbs to soil particles or binds with other minerals; however, a study with spinach grown in pots found that urine fertilizer increased the available pools of P in the soil (Rumeau et al., 2023). Another study found increased available P from urine-derived struvite in a field experiment with maize (Gell et al., 2011). Despite these advances, urine-derived P soil dynamics under a variety of crops, management strategies, and soil types is insufficiently investigated (Harder et al., 2019). To our knowledge, using human urine fertilizer in a perennial system, which has the potential to both incorporate P into the available pool and retain P and other recovered nutrients via their deep root structures, has not yet been studied.

In addition to the biophysical effects of urine fertilizers, the disconnect between understanding the ecological benefits of urine recycling and implementing the practice remains to be fully explored. Many recent reviews highlight the potential of reclaiming nutrients (Larsen, Gruendl, et al., 2021; Martin et al., 2022; Randall & Naidoo, 2018; Simha & Ganesapillai, 2017) and propose scenarios for integrating urine diversion into existing infrastructure (Hilton et al., 2021; Maiza et al., 2024). Surveys also indicate that people appear to be generally favorable towards urine collection and fertilizer use (Ishii & Boyer, 2016; Lamichhane & Babcock, 2013; Segrè Cohen et al., 2020; Simha et al., 2021); however, urine recycling has not been implemented on a large scale, especially in the U.S. (Aliahmad et al., 2023).

Previous studies have shown that pharmaceuticals and other organic micropollutants are a common concern, and much of the current work in the field is on contaminant removal technologies (Almuntashiri et al., 2021; Köpping et al., 2020; Larsen, Riechmann, et al., 2021; Li et al., 2023; Özel Duygan et al., 2021; Simha & Ganesapillai, 2017). Social norms and opinions of peers are also strong predictors of acceptance, and both are influenced by exposure to nutrient reclamation (Simha et al., 2021). In Sweden and Switzerland, two countries pioneering the technology, pilot projects were crucial to the expansion of urine recycling systems (Aliahmad et al., 2023). There are limited examples of projects in the U.S., however, where there are potentially unique barriers and regulatory challenges. Important work has been done in recent years to assess the concerns and considerations of different demographic groups (Schreiber et al., 2020, 2021), but there have been few opportunities to learn from people who have personally participated in a urine diversion project in the U.S.

To build on nascent work in the U.S., we started the first known project in Kansas on urine nutrient reclamation in the workplace. We had two main goals: (1) Investigate the potential of human urine to increase available P in a silt loam soil and evaluate its effect on other soil nutrient concentrations and on the biomass of the perennial legume alfalfa (*Medicago sativa*); and (2) Identify potential concerns and barriers that might limit participation in future projects, as well as actions and information that best support participation. We hypothesized that urine would increase available soil P and subsequently increase alfalfa biomass compared to water and control treatments. As a small pilot study, this project also identified regulatory and logistical challenges for conducting urine nutrient reclamation projects in the U.S., which may benefit larger scale and community-based projects moving forward.

Project Design and Methods

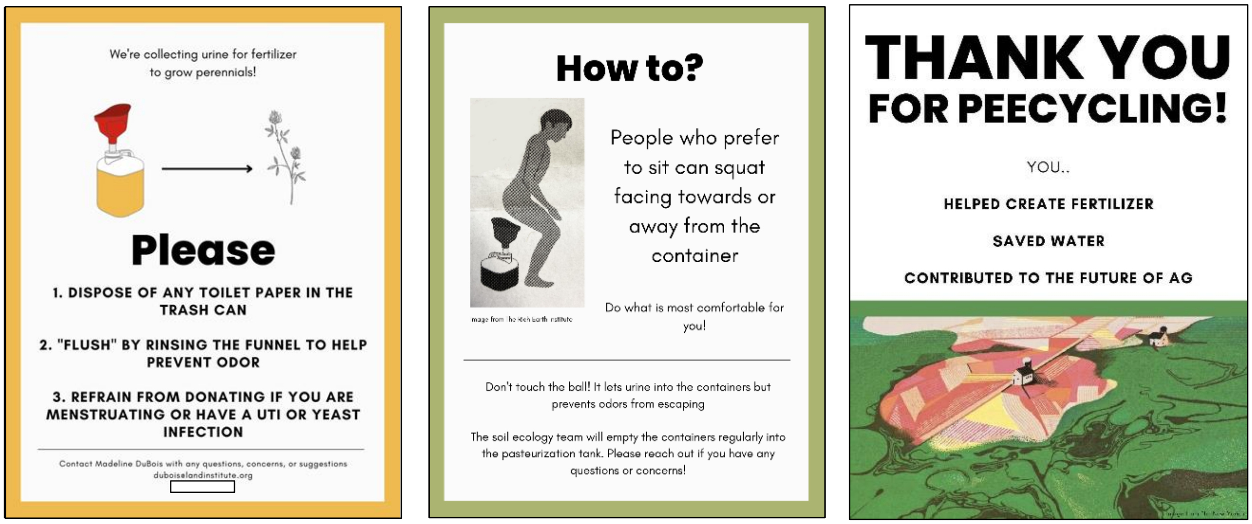
The study was based at The Land Institute (TLI), an organization in Kansas working to develop perennial grain agricultural systems, with logistical advising from Rich Earth Institute. In March 2023, the TLI soil ecology team invited TLI staff to a seminar that contextualized the project within the larger scope of their work. This seminar provided background on the importance of P in agriculture and current P management practices, presented urine diversion as part of the solution for sustainable P cycling alongside perennials, and outlined the opportunity to participate in the project. We installed urine collection units (Figure 1) based on a design used by Rich Earth Institute in five bathrooms on TLI's campus with accompanying signage (Figure 2). We stored urine from collection units in a sealed tank for more than 1 month above 20°C for passive pasteurization in accordance with World Health Organization (WHO) guidelines for urine fertilizer use on fodder crops (WHO, 2013, p. 70).

Field Study

The field study site was located at the Perennial Agriculture Project field station in Lawrence,

Figure 1. Urine Collection Unit Modeled After the Design by Rich Earth Institute

Figure 2. Informational Signage Hung in the Bathrooms Next to the Collection Units



Kansas (39.002039, -95.319313). The soil type is Sharpsburg silt loam with pH values ranging from 5.5 to 6.3. The field has areas with low available P (Appendix Table A3) which may have contributed to poor establishment historically. The field was sown with alfalfa (*Medicago sativa*) in fall 2021. Three treatments consisting of (1) urine fertilizer, (2) water control where water was applied in the same volume as urine, and (3) a control with no manipulation were arranged in a randomized block design with 6x6 m^2 plots. Using a trailer with a 378 L tank and pump (Figure 3), urine fertilizer was applied three times following the alfalfa harvest (Figure 4). A target rate of 20 kg $hectare^{-1}$ (ha) for the field season was determined based on recommended P additions of 30–40 lbs ac^{-1} of P_2O_5 (19.3 kg ha^{-1}) for a field with established, non-irrigated alfalfa stands and "medium" available P (13-25 ppm) (Shroyer et al., 1998). The volume of urine applied per plot (0.185 ha-cm) was calculated assuming a P concentration of 0.36 g P L^{-1} as reported by Rich Earth as a composite result from their community collection program (Rich Earth Institute, n.d.). Actual urine P content was 0.15 g P L^{-1}, likely due to the rinse water used to clean collection units to limit odor. This resulted in P application rate being half the target amount at 10.9 kg P ha^{-1}.

To assess changes in soil nutrients, one composite soil sample (0-20 cm) consisting of six cores per plot was collected with a step probe (2.5 cm diam.) before (May) and after (November) the 2023 field season and analyzed for total and available phosphorus (P), calcium (C), potassium (K), magnesium (Mg), sodium (Na), nitrate (NO_3), ammonium (NH_4), and total nitrogen (N) content at the Kansas State University Laboratory (in Manhattan, Kansas). We assessed aboveground biomass by clipping alfalfa from one 1x1 m^2 quadrat per plot to a height of 10 cm from the soil surface with a sickle (4 weeks and 7 weeks after urine application) (Figure 4); samples were dried (60°C, 48 hrs) prior to being weighed.

Figure 3. The Urine Application Trailer with the 378 L Tank, Pump, and Small Boom

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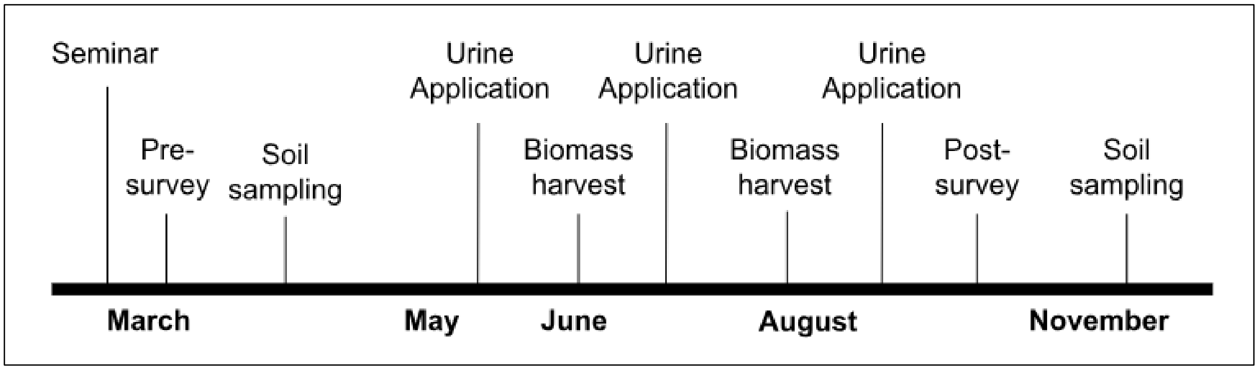
Figure 4. Timeline with Approximate Dates of the Pre-Project Seminar, Survey Distribution, Soil Sampling, Biomass Harvests (Just Before the Field was Mowed), and Urine Applications



Data Analysis

Statistical analyses were performed using R software (R Core Team, 2024, v 4.4.0). We first confirmed normality with a Shapiro-Wilk test. To assess whether there was a treatment effect on aboveground biomass or soil nutrients, we conducted an analysis of variance (ANOVA) test using *lme4* (Bates et al., 2015) and Tukey's HSD post-hoc test with pairwise comparison using *emmeans* (Lenth, 2024) for any differences deemed significant at $\alpha < 0.05$ (Appendix Table A4). In all cases, the block was treated as a random variable with treatment as a fixed effect. Changes to soil nutrients were evaluated based on the difference between the final and baseline soil sample, and biomass harvests were evaluated per plot as the sum of the two harvests.

Survey and Pilot Project Evaluation

To evaluate the social impact of the pilot project and improve the quality of future efforts, we invited all TLI staff to participate in optional, anonymous online pre- and post-project surveys with a two-week window for each. Surveys were hosted on Airtable and distributed via Slack before urine collection began in March 2023 and after the field season concluded in August 2023. Both surveys were compiled and presented to TLI staff in a return-of-results seminar in February 2024.

The initial survey sought responses about whether participants had attended the informational seminar, their likeliness to contribute urine to the project (0–5 scale), and open-ended questions related to any reservations or suggestions they had (see the questionnaire in Appendix Table A1). The final survey inquired about whether respondents had donated urine to the project and how the project affected their perception of the viability of urine nutrient reclamation in current or future agricultural systems (Appendix Table A2). The survey also assessed the likelihood of future participation and perceptions of how the project related to the broader mission of TLI.

To evaluate the survey data, three members of the project team individually coded participant responses ($n = 20$ pre-, $n = 13$ post-survey) and identified common themes and phrases. Quantitative responses were summarized as percentages; common themes were arrived upon by consensus for qualitative responses. All participants whose responses were included in this analysis consented to be quoted anonymously.

Results and Discussion

This study provides a rare U.S. example of a project that enhances our understanding of both the biophysical effects of urine fertilizer and the experience of the study participants. We first outline the physical effects urine fertilizer had on alfalfa biomass and soil nutrients in the field experiment, and then summarize our findings from the staff survey that could inform future work.

Urine Fertilizer Had No Effect on Biomass

We hypothesized that urine fertilizer would enhance forage biomass of alfalfa beyond a water-only control by supplying potentially limiting P

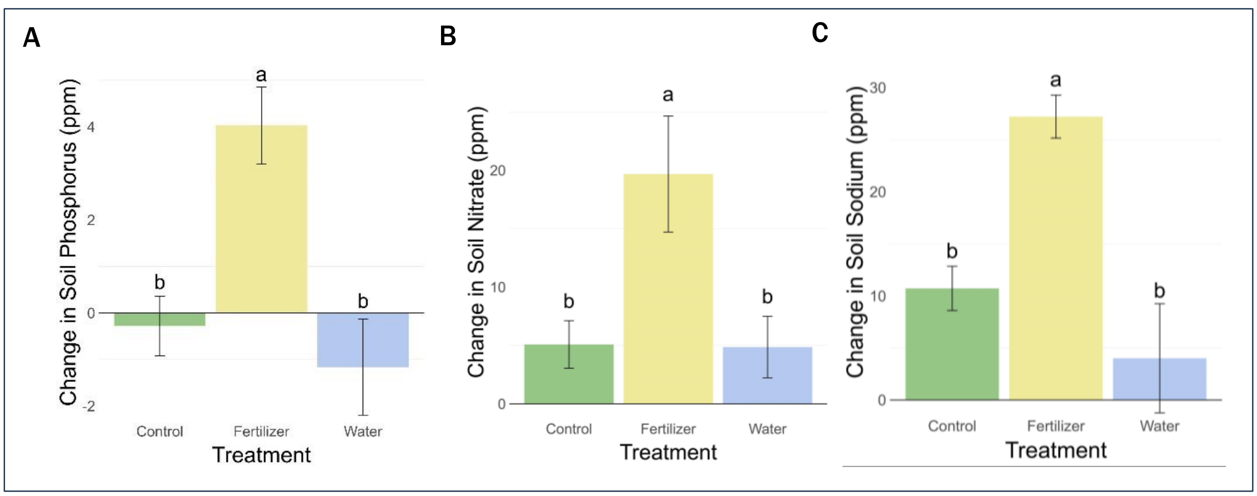
(Crews, 1993). There were no differences in yield, however ($p = 0.9$, *data not shown*). This result contrasts with many studies that found urine fertilizer increased biomass in crops such as maize, kale, beets, lettuce, and spinach (Andersson, 2015; Chrispim et al., 2017; Pradhan et al., 2010; Semalulu et al., 2011). We may not have observed an effect in this instance as our application rate may have been insufficient to alleviate P-limitation, having applied only half the recommended P and raised the soil P to only a "medium" concentration (Shroyer et al., 1998) (Table 1). Two biomass harvests may also have been insufficient to observe possible effects, especially as logistical constraints prevented a third harvest at the end of the growing season following the final fertilizer application.

Urine Fertilizer Increased Soil Available Phosphorus, Nitrate, and Sodium

As hypothesized, urine fertilizer increased soil available P (using the Mehlich-3 test) (Figure 5A). Prior to this study, it was not clear whether urine fertilizer would primarily contribute to the inorganic unavailable soil P (Syers et al., 2008), but our results are consistent with findings from a greenhouse study with spinach showing urine-P contributed primarily to the available and slightly available soil P (Rumeau et al., 2023).

The fertilizer also significantly increased nitrate (NO_3-N) (Table 1; Figure 5B). We applied 192 kg N ha^{-1} (urine fertilizer N application is not recommended after the establishment year for alfalfa) (Shroyer et al., 1998), so the increase in soil NO_3 is

Figure 5. Difference Between Baseline (May) and Final (November) Soil Samples with Three Treatments
The three treatments are control (green; no application), fertilizer (yellow; 3 urine applications totaling 10.9 kg P ha^{-1}, 192 kg N ha^{-1}), and water (blue; addition at equivalent liquid volume as urine (0.185 ha-cm)) for (A) available soil P (Mehlich-3), (B) soil NO_3, and (C) soil Na



Bars represent standard error. Letters denote significant differences among treatments ($p \leq 0.05$).

Table 1. Average Baseline and Final Soil Concentrations of P, NO_3, and Na, the Three Nutrients with Significant Treatment Effects

Treatment	Initial P	Final P	Initial NO_3	Final NO_3	Initial Na	Final Na
Control	15.3 (6.1)	15.1 (5.7) b	17.1 (1.4)	22.2 (1.5) b	24.2 (1.8)	34.9 (2.8) b
Fertilizer	19.0 (6.0)	23.0 (5.1) a	14.8 (3.8)	34.5 (8.4) a	24.8 (1.4)	52.1 (3.2) a
Water	19.0 (6.0)	17.9 (5.4) b	15.9 (1.7)	20.8 (2.6) b	25.9 (2.7)	29.9 (3.5) b

Concentrations are in parts per million (ppm) with standard error in parentheses. Different letters indicate statistically different changes in concentration (Tukey's HSD, alpha = 0.05).

expected. Given the high application rate, we may have expected an even greater increase in soil N, but much of the applied N may have volatilized quickly as N volatilization increases with temperature, wind, and dry conditions (Hargrove, 1988). Our sprayed applications at temperatures between 35℃ and 40℃ with dry winds and no immediate rainfall would have been likely to experience losses. A recent greenhouse study with human urine simulated losses to volatilization of greater than 50% of the N applied (Rumeau et al., 2023), and 31% of N was lost from urine fertilizer that was similarly broadcast-applied in a field trial (Noe-Hays, 2020), indicating that N losses should be further studied and mitigated. The increase in soil NO_3 is notable, as this form of N is readily utilized by alfalfa and would likely have a greater benefit for crops other than alfalfa that are not N-fixing. NO_3 is also a form of N easily leached from soil (Blumenthal & Russelle, 1996; Hussain et al., 2020). Perennial roots have been repeatedly shown to reduce N leaching by one to two orders of magnitude compared to annuals (Culman et al., 2013; Huddell et al., 2023; Jungers et al., 2019), underscoring the promise of pairing urine fertilizers with perennials to close nutrient cycles.

While increases in soil P and N boost soil fertility, the urine fertilizer also resulted in an agronomically undesirable increase in soil sodium (Na) (Figure 5C). Urine's unintended effect on soil sodicity, or the proportion of sodium relative to other cations in the soil, that has been documented in other studies is a concern, especially in semi-arid and arid regions such as Kansas (Kassa et al., 2018; Mnkeni et al., 2008; Rumeau et al., 2023; Sene et al., 2019). There were no treatment differences for any other nutrients, but changes under continuous application have not been fully explored and should be investigated further (Rumeau et al., 2023).

Advancing Nutrient Recovery from Urine Will Require Investment in Efforts to Educate, Understand Contaminant Risk, and Normalize the Practice

Staff members reported having an overall positive experience participating in urine collection, but the survey results revealed several key areas for investment to improve future efforts. Many participants learned about urine diversion and the need for more sustainable P sources in agriculture through exposure to this project. Our results corroborate previous findings that many people support urine diversion and reuse once they are exposed to the concept (Beler Baykal, 2019; Lienert & Larsen, 2010; Simha et al., 2021). However, nearly half of respondents were previously unaware of urine source separation as a solution to unsustainable nutrient management. One person mentioned that "prior to my participation, I imagined that the obstacles to implementing a project like this were simply too complicated in a culture that is so averse to waste recycling in general, so it was really exciting to see this idea put into action." Despite this study taking place at a research organization dedicated to sustainable agriculture systems, nearly half of participants reported that this project was their first exposure to information about current unsustainable P management and about how conventional wastewater treatment does not typically remove pharmaceuticals or organic pollutants (Fatta-Kassinos et al., 2011). This underscores the need for education on current unsustainable practices and the opportunity that urine diversion offers, particularly given that our results were consistent with findings from other studies that sustainability and conserving resources motivated participation in urine cycling projects (Lamichhane & Babcock, 2013; Simha et al., 2021).

Our surveys identified one potential barrier to participation in a urine diversion project: concern about contaminants from urine posing a health or environmental risk. This is consistent with previous studies and highlights the need for continuing research on the fate of pharmaceutical and other micro-pollutants, prioritizing contaminant mitigation strategies, and conducting participatory research to characterize what "safety" means to people (Lienert et al., 2003; McConville et al., 2023; Pahl-Wostl et al., 2003). As there were many questions posed in the surveys following the research seminar but few asked in person, we inferred that another potential barrier to participation may be social discomfort about asking clarifying questions. Other less frequent but common concerns centered around the unfamiliar collection device and uncertainty around when it is appropriate to participate while on medications, with a urinary tract infection, or while menstruating. We therefore believe that future projects will benefit from a collection unit design resembling familiar toilets, clear guidelines on when and how to donate, and an option to submit anonymous feedback and questions.

Lastly, one of the most important takeaways from our pilot study was the sense of personal agency that this project afforded participants. As a result of their experience, several people approached project facilitators to express an interest in collection units for their home. Also, many people reported that while they were initially disheartened by the huge challenges with P management, participating in this project was inspiring and gave them actionable steps that made a solution feel more accessible. In the post-project survey, one participant wrote, "It's really empowering to feel the literal parts of my body somehow contributing to the well-being of the ecosystem I am a part of, particularly when it's something typically considered unwanted 'waste.'"

Regulatory Challenges

One of our goals in reporting our experiences is to contribute to the feasibility of future projects. We would have benefited if there had been more prior project examples, particularly those that set a regional regulatory precedent. For the 2023 field season, we obtained written permission from the public health department to proceed with our small-scale study. In 2024, county regulators determined that no single individual had the authority to grant permission for an experiment involving applying human urine to soil, and we have faced significant challenges obtaining approval with no clear regulatory pathway for urine fertilizer in Kansas. To make progress in diverting nutrients from our waste system back to agriculture, we need national guidelines giving legal authority for municipal and state entities responsible for wastewater treatment and safety to consider urine separately from biosolids.

Conclusions

Three applications of urine successfully increased available soil P in a slightly acidic, silt loam soil, although the treatment had no effect on short-term aboveground biomass. This demonstrates the feasibility of pairing urine fertilizer with perennial crops as part of the strategy to increase circularity of critical nutrients such as P in the food system. Future research should explore biomass effects over multiple seasons, the forms that human urine P is incorporated into in the soil, nitrate volatilization losses, and the implications of sodium increases across locations and soil types. While the survey sample size was small and not generalizable, the results reinforce findings from similar studies that concerns about contaminants are most common and thus a potential barrier to adoption. Research on ways to mitigate pollutants and understand their effects should be prioritized. This pilot project also highlights the need for more awareness of and education about P management, wastewater treatment, and the potential of urine diversion and reuse as fertilizer. Additionally, policy that specifically defines urine separately from wastewater and development of a clear regulatory pathway for urine fertilizers in the U.S. are critical. We nonetheless saw that engaging with urine collection provides a sense of agency and helps people feel empowered in light of overwhelming environmental challenges. This study provides an example of a project that we believe can contribute to much-needed community-based and workplace projects at a larger scale in the U.S. moving forward.

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Appendix

Table A1. Initial Survey Questionnaire and Type of Answer Choices

No.	Survey statements	Answer choices
1	Did you watch the seminar?	Yes or no
2	Based on what you've learned so far about this project, how likely are you to donate your urine?	1–5 (unlikely to very likely)
	(3–5) If you plan to donate urine, why are you planning to do so?	Open ended
	(1–2) If you answered 1 or 2, why are you unlikely to donate?	Open ended
3	Do you have any concerns with donating your urine or with using urine as a fertilizer?	Open ended
4	If urine fertilizers are to be used on crops, which crops do you feel would be appropriate for this use?	Multiple choice
	a) all crops for which the nutrient profile meets their needs	
	b) forage crops used for animal feed	
	c) pasture	
	d) vegetable crops	
	e) fruits, berries, nuts	
	f) non-edible crops (such as flowers)	
5	Do you have any suggestions for how to improve this project? Is there anything that would make you feel more comfortable about participating?	Open ended
6	Anything else that you would like to share?	Open ended

Table A2. Final Survey Questionnaire and Type of Answer Choices

No.	Survey statements	Answer choices
1	Did you use a urine diverting toilet on campus?	Yes or no
	Based on this experience, how likely would you be to donate urine in the future?	1–5 (unlikely to very likely)
	At this point, do you have any concerns with donating your urine or with using urine as fertilizer?	Open ended
2	Did this project change your perception of the role or viability of urine as fertilizer in our current and future agricultural systems? If so, how?	Open ended
3	Do you see this project relating to our work at TLI? Please elaborate if so!	Open ended
4	Would you be interested in seeing this project continue?	Open ended
5	Did you learn anything through exposure to this project? If so, what did you learn? If not, why not?	Open ended
6	Did your participation in urine collection change your thoughts or feelings about your role in the ecosphere?	Open ended
7	Do you have any suggestions for how to improve this project if it is to be continued in the future?	Open ended

Table A3. Baseline and Final Soil Sample Nutrient Levels in Parts per Million (ppm), Reported as Treatment Averages with Standard Error Below in Parentheses

		P	Ca	K	Mg	Na	NH_4	NO_3	TN	TP
Initial	Control	15.3 (6.1)	2436.3 (142.2)	229.8 (15.9)	349.9 (41.3)	24.2 (1.8)	7.6 (1.6)	17.1 (1.4)	2010.8 (85.8)	498.5 (42.5)
	Fertilizer	19.0 (6.0)	2528.3 (129.1)	250.2 (16.3)	376.3 (34.6)	24.8 (1.4)	16.1 (4.7)	14.8 (3.8)	1940.2 (98.3)	547.5 (25.5)
	Water	19.0 (6.3)	2462.2 (120.8)	235.4 (17.9)	364.1 (36.1)	25.9 (2.7)	9.1 (2.6)	15.9 (1.7)	1866.4 (165.9)	454.5 (2.4)
Final	Control	15.0 (5.70)	2587.5 (198.1)	241.9 (28.3)	369.5 (49.1)	34.9 (2.8)	4.8 (0.7)	22.2 (1.5)	2214.7 (69.3)	475.3 (21.6)
	Fertilizer	23.0 (5.1)	2659.3 (172.2)	279.0 (43.6)	380.2 (42.2)	52.1 (3.2)	12.1 (6.7)	34.5 (8.4)	2186.4 (87.3)	531.5 (70.0)
	Water	17.9 (5.4)	2660.3 (152.3)	255.9 (23.2)	387.2 (35.3)	29.9 (3.5)	4.8 (0.4)	20.8 (2.6)	2061.3 (66.6)	496.3 (76.8)

Table A4. Results of the Mixed Model Analysis of Variance (ANOVA) F-statistic for Differences in Soil Concentrations of P, Na, and NO_3

	F - statistic		
ANOVA results	Average difference in P (ppm)	Average difference in Na (ppm)	Average difference in NO3 (ppm)
treatment	17.8 **	11.8 **	12.8 **

** Significant at the .01 probability level.