# Title: Urine Diversion for Nutrient Recovery and Micropollutant Management: Results from a Regional Urine Recycling Program

Abraham Noe-Hays[1*], Kim Nace[1], Neil Patel[1], Rebecca Lahr[2], Heather Goetsch[2], Rachel Mullen[3], Nancy Love[2], Diana Aga[3], Charles Bott[4], Betsy Foxman[5], Jose Jimenez[6], Ting Luo[5], Kirtana Ramadugu[5], Krista Wigginton[2]

[1]Rich Earth Institute, 44 Fuller Drive, Brattleboro VT 05301
[2] Department of Civil and Environmental Engineering, University of Michigan, 1351 Beal Ave, EWRE, Ann Arbor, MI 48109
[3]Department of Chemistry, University at Buffalo, State University of New York, Buffalo, NY 14260
[4]Hampton Roads Sanitation District, 1434 Air Rail Ave, Virginia Beach, VA 23455
[5]Department of Epidemiology, University of Michigan 1415 Washington Heights, Ann Arbor, MI 48109
[6]Brown and Caldwell, 2301 Lucien Way, Suite 250, Maitland, FL 32751
***Email: abe@richearthinstitute.org**

## ABSTRACT
Source separation of urine is a novel strategy that facilitates improved nutrient recovery and micropollutant management. The Rich Earth Institute operates the United States' first regional urine recycling program, collecting source-separated urine from households and producing a sanitized fertilizer product for use by local farmers. The purpose of this program is to provide practical experience and quantitative data on all stages of the urine recycling process, and to create a platform to allow detailed research into specific aspects of the process in a real-world context. Current research topics at the Institute include the fate of pharmaceutical and biological constituents when urine is used as fertilizer, the effect on crop yield of urine fertilizer in comparison with synthetic fertilizer, and methods for transforming and concentrating urine to reduce the cost of storage and transport.

## KEYWORDS
Resource recovery, nutrient recovery, source-separated urine, urine-based fertilizer

## Introduction
Urine contributes the majority of nitrogen and phosphorus found in municipal wastewater (Lienert and Larsen 2007). Removing urine at the source results in lower energy requirements at wastewater treatment plants, a reduction in fresh water consumption from toilets, a wastewater composition that favors biological N removal (Jimenez et al. 2012), and an opportunity to collect contaminants that are concentrated in urine (i.e., pharmaceuticals) in a less complex and reduced-volume waste stream. Source-separated urine also has the potential to become a valuable and sustainable nutrient source for agriculture applications.

Although the topic of urine separation has received considerable interest around the world as an area of research and a subject of demonstration projects, most of this work has been done outside of the United States. In fact, a recent WERF report on the status of urine separation noted that the lack of U.S.-based pilot studies was hindering the progress of urine-diversion development in the U.S. (Fewless et al. 2011).

The Rich Earth Institute was founded in 2011 by Abraham Noe-Hays and Kim Nace in order to fill this research gap. An independent not-for-profit research and demonstration organization based in in Brattleboro, Vermont, the Institute operates the Urine Nutrient Reclamation Project, the nation's first community-scale pilot program for the collection, treatment, and beneficial reuse of urine as an agricultural fertilizer. Through the implementation and ongoing expansion of this program, we are gathering practical knowledge and experience concerning the management of the entire urine recycling process, as well as conducting research into specific aspects in greater detail.

In addition, the Institute conducts extensive outreach and education to raise awareness of urine diversion and beneficial reuse, particularly with regulators, policy makers, and infrastructure managers. Because of the potential for this strategy to solve nutrient-related wastewater challenges and protect natural resources within our area of operation in Vermont, the initiative has received endorsements from numerous local bodies including the Brattleboro Department of Public Works, Brattleboro Agricultural Advisory Committee, Windham Solid Waste Management District, Windham Regional Commission, and Chief Operator of the Brattleboro Wastewater Treatment Plant.

In this manuscript, we describe the Rich Earth Institute's work to develop a U.S.-based pilot urine recycling program, with particular attention to practical aspects of urine collection using special bathroom fixtures, transport to nearby farms by a licensed septage hauler, a state-approved sanitization process, testing to determine fertilizer content, and application of the resulting product to agricultural fields, including successes and areas in need of improvement. We will also discuss research into the agronomic value of urine as fertilizer, and a collaboration funded by WERF to examine the persistence of biological and pharmaceutical constituents of urine when urine or urine-derived products are used as fertilizer to grow edible crops.

***Urine collection***

Participants use one of two methods for urine diversion: 1) a stand-alone waterless urinal with an exchangeable tank, or other small collection container, or 2) a urine diverting toilet plumbed to a storage tank, typically 1000 L (270 gallon) capacity located in the basement or in-ground. Participants using portable containers bring full containers to a central depot with a pump station, while a septage truck collects urine from the large tanks. An estimated 200 individuals have participated since the program's inception in 2012, collecting approximately 8,000 gallons of urine.

The stand-alone urinals consist of a funnel assembly that screws tightly onto a 20 L polyethylene jug. Odors are prevented from leaving the container by a ping pong ball that sits inside the funnel and floats up when urine is added and then settles down to seal the opening after the urine has passed. A breather tube allows pressure equalization within the collection container while minimizing odor diffusion or bulk air movement, and a fabric sleeve covers the container. The urinals were devised as a simple and inexpensive way to quickly gather enough urine from a group of dedicated volunteers to begin processing urine and conducting field trials. Although not proposed as a permanent or mainstream method for urine collection, these simple devices have proven very popular with both male and female participants, some of whom keep them for convenience in places without easy toilet access, such as bedrooms, studios, job sites, etc., while others keep them beside the commode in the bathroom.

Several participants own urine-diverting toilets, which require very little involvement on the part of the user in terms of maintenance or other management. The toilet bowl area of a urine-diverting toilet is divided, with the front half forming a basin with its own drain that is plumbed to the collection tank. When both male and female users are seated, urine naturally falls into the urine collection portion of the bowl and then flows to the collection tank. The average time period to fill a 1000 L tank, as reported by one three-person family participating in this project, has been 8 months.

Buy-in among urine donors has been high, with over 200 households participating since the project's inception and reporting high levels of satisfaction and investment in annual urine donor surveys. The project has received endorsements from the Windham Regional Planning Commission, Brattleboro Agricultural Advisory Committee, Brattleboro Department of Public Works, and Chief Operator of the Brattleboro Wastewater Treatment Plant. Active outreach has been critical to this success.

***Transport and storage***

A local septage hauling company, Best Septic Services of Westminster, provides urine transport for the project. Their innovative work developing methods for the practical and economical transport of urine using standard industry equipment was featured in Pumper Magazine (Wysocky, 2015). One of the company's portable toilet service trucks is now configured with a dedicated tank compartment for urine, allowing the driver to make urine collections while traveling the company's existing portable toilet service route. The company's urine transport fee of \$0.10/gallon is lower than their standard rate for transporting septage to a treatment facility because there is no tipping fee at the participating farms, which accept the urine free of charge due to its fertilizer value.


*Figure 1.* Pumping urine from the collection depot using a vaccuum truck for transport to a participating farm.

A significant practical challenge of this project is the expense and logistics of storing the collected urine. Because the ammonia in stored urine is volatile, it is necessary to keep it in closed tanks, and since the demand for fertilizer is seasonal, storage tanks must be sized to hold urine until the growing season, driving up infrastructure costs. Collected urine is stored in palletized 1000 L (265 gallon) polyethylene tanks (IBCs) at participating farms. These tanks are available reconditioned for \$100 each, for a unit cost of \$0.36/gallon of storage capacity. In the short term tankage is the largest expense, though assuming a ten-year service life and one filling per year, tankage costs would drop to \$0.04 per gallon of urine recycled. Even so, this cost is substantial, and the economics of urine recycling could be improved by methods for either concentrating the urine to reduce its volume, or stabilizing the nitrogen so that it could be held in less costly unsealed storage facilities.

Various strategies have been tested for nitrogen stabilization and urine volume reduction, including evaporation, freeze-thaw cycling, reverse osmosis, and biological nitrification. (Maurer *et al.* 2006)

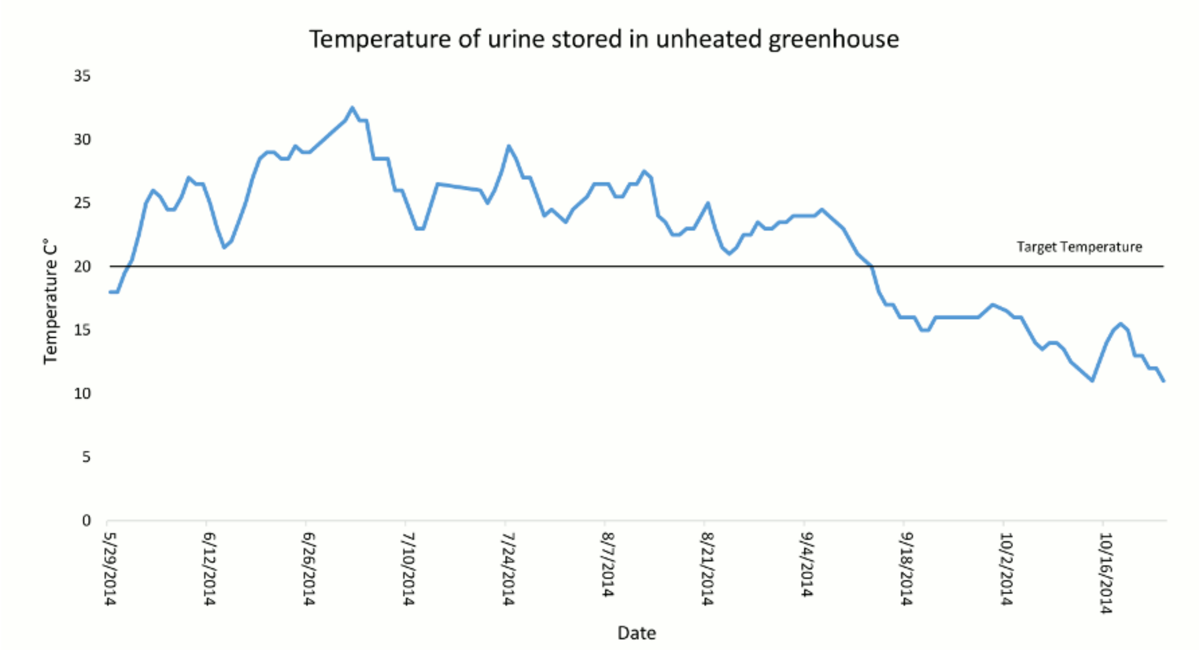
The Rich Earth Institute is experimenting with co-composting urine along with other feedstocks, in order to evaporate the excess water from the urine and assimilate the dissolved nutrients into a stabilized compost product. This product could be stored in open-air windrows until use, resulting in substantially reduced storage costs compared with pure urine, which must be held in expensive sealed tanks. In ongoing trials, funded through the USDA SARE program, the Institute is using a benchtop reactor and three 1.8 $m^3$ outdoor piles to assess several feedstocks and aeration regimes for their ability to evaporate excess moisture and retain nitrogen. Data from this trial will be available for presentation at WEFTEC. The Institute has also recently acquired a 300 L/day reverse osmosis system, and has begun experimentation with direct water removal from urine.

***Sanitization***

Prior to land application, all urine is sanitized using one of two methods that have been approved in the Institute's permit from the Vermont Department of Environmental Conservation: 1) exposure to naturally-forming free ammonia and elevated pH during storage at 20 °C for 30 days (Höglund 2001), or 2) pasteurization following a time-temperature formula including 70 °C for 30 minutes or 80 °C for 1.2 minutes. This is done to eliminate pathogens that may be present in the collected urine, particularly as a result of fecal contamination.

Of the two treatment methods, storage at 20 °C for 30 days proved to be technically the simplest, requiring only the installation of a data logger with submersible temperature probes. However, even with tanks enclosed in an unheated greenhouse**,** target temperature was only reached between June and September (Figure 2), limiting this method's utility in cool climates. In warmer regions the low capital cost and simplicity of execution could make this method more desirable.

*Figure 2.*




Pasteurization has the advantage of speed and cold-weather operation. The Institute has developed two custom-built urine pasteurizers for the project, the first heated by solar thermal panels and having a 160 L/day capacity, and the second using electric resistance heating and a heat recovery system and having a 3000 L/day capacity. Energy consumption for the electrically heated pasteurizer is about 14 Wh per liter pasteurized, which at current retail electricity rates costs about $0.002/L.

The electric resistance pasteurizer is operated under a 10-year permit issued by the State of Vermont that allows the unit to be used throughout the state. It is a mobile unit, mounted on a lightweight 4' x 8' trailer, and is fully automated with automatic temperature and flow controls, redundant high water cutoffs, and overflow containment. Previously to the current permit, treatment was allowed through a short-term discretionary permit. The current permit is the result of several years of collaborative discussions with state regulators who eventually found a pathway for permitting urine pasteurization under rules that had never anticipated a project of this nature. Fecal coliform and heavy metal testing are required prior to land application, though these requirements may be modified in the future if cumulative test results justify a change.

***Nutrient and heavy metal content***

Heavy metal levels are shown in Table 1. As reported by others (WHO 2006), heavy metal levels in urine were extremely low, orders of magnitude below the levels allowed in our permit. Potential contamination of the urine by heavy metals leached from the various alloys present in the hauling equipment was originally an area of concern. However, regular analysis has shown metals levels to be consistently less than 1/1000 of the permitted concentration.

| | Cu | Zn | Cr | Cd | Pb | Ni | Mo | Ar | Se | Hg |
|---|---|---|---|---|---|---|---|---|---|---|
| **Max** | 0.35 | 0.37 | 0.03 | 0.25 | 0.15 | 0.035 | 0.174 | <0.05 | <0.5 | 0.00027 |
| **Min** | 0.09 | 0.14 | 0.01 | <0.005 | <0.005 | <0.008 | <0.05 | <0.05 | <0.5 | 0.0002 |
| **Average** | 0.22 | 0.26 | 0.02 | | | | | | | |
| **Std.Dev.** | 0.08 | 0.08 | 0.01 | | | | | | | |
| **Sample Size** | 9 | 9 | 6 | 6 | 6 | 6 | 3 | 3 | 3 | 3 |

*Table 1.* Concentration of heavy metals in urine collected between 2012 and 2015.

Nitrogen levels in urine are high in comparison with phosphorus and potassium (Table 2), making urine fertilizer well suited for crops with high nitrogen demands, such as mid-season fertilization of hay crops (Jokela et al. 2004). In vegetable field trials, urine meets the nitrogen needs of crops and is supplemented with triple superphosphate and KCl to meet potassium and phosphorus requirements.

| | NO3-N | NH4-N | Ca | P | K | Mg | Na | Al | Fe | Mn | B | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Max** | 2.30 | 6690 | 72.13 | 391 | 1919 | 27.13 | 1851 | 1.60 | 0.34 | 0.004 | 3.35 | 766 |
| **Min** | 0.02 | 4411 | 6.60 | 275 | 1300 | 0.13 | 1210 | <0.02 | 0.03 | <0.005 | 0.80 | 286 |
| **Average** | 0.95 | 5477 | 25.93 | 355 | 1575 | 6.54 | 1511 | | 0.16 | | 1.59 | 448 |
| **Std.Dev.** | 0.64 | 648 | 22.39 | 34.0 | 205 | 10.98 | 219.6 | | 0.13 | | 0.74 | 152 |
| **Sample Size** | 10 | 11 | 10 | 12 | 11 | 10 | 9 | 9 | 9 | 9 | 9 | 9 |

*Table 2.* Concentration of nutrients and light metals in urine collected between 2012 and 2015.

***Persistence of biological and pharmaceutical constituents***

The Rich Earth Institute is currently involved in a WERF-funded study of the presence and persistence of pharmaceutical and biological residuals in crops and agricultural soils following use of urine-based fertilizer, in partnership with the University of Michigan, University at Buffalo, Hampton Roads Sanitation District, and Brown and Caldwell. The study includes the first agronomic trial under field conditions to examine the fate of pharmaceuticals from source-separated urine.

This manuscript describes the methods used for collection and treatment of urine for this trial, the layout of the field trial plot, and the construction and installation of the lysimeters used for collecting soil water. Another paper presented at WEFTEC by Heather Goetsch of the University of Michigan describes findings from the study's first year.

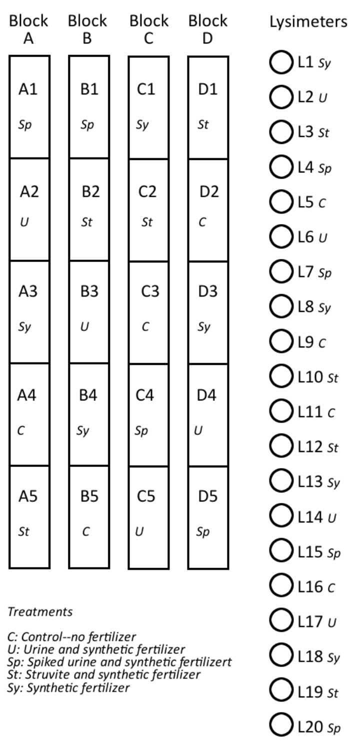
The WERF study is a comprehensive examination of the presence and persistence of the biological and pharmaceutical constituents of urine and urine-derived struvite (magnesium ammonium phosphate). The study characterizes the bacterial and viral populations in urine and its derivatives, tracks 14 pharmaceuticals commonly found in wastewater treatment plant effluent, and quantifies their concentrations in source-separated urine and urine-derived struvite. Urine, urine-derived struvite, and urine spiked with an additional 1 ppm of the target pharmaceuticals, are used to fertilize lettuce and carrots *in situ.* Pharmaceutical and biological concentrations in edible plant tissue, soil, and soil water intercepted by lysimeters at a depth of 60 cm are monitored over a period of four crop cycles spanning two years.

Lettuce was chosen for the study due to the fact that pharmaceuticals can be transported to lettuce leaves where they accumulate due to evapotranspiration through the leaf surface (Calderon-Preciado *et al.* 2012). Carrots were chosen in order to include a root tissue that does not experience appreciable levels of evapotranspiration. The lettuce variety was "Two Star" and the carrot variety was "Nelson", obtained from Johnny's Selected Seeds in Albion, Maine.

Urine for this study was sourced from as wide a population as possible, with each batch of urine containing contributions from 1,000 to 2,500 individuals. Urine came from portable, unisex, public toilets (modified to be used for urination only) that were deployed at outdoor summer events, and from waterless urinals in a men's bathroom at a highway rest stop. These venues served as not only a source of urine, but also an outreach opportunity to educate the public on the problem of nutrient pollution and the benefits of urine diversion.

Urine is also being collected at the Hampton Roads Sanitation District office from waterless urinals and a urine-diverting toilet. Struvite manufactured from this urine using the Ostera process will be analyzed for the study, though it will not be used on the test plots.

*Figure 3.* 2015 planting bed and lysimeter layout.



Lettuce and carrots are being grown sequentially on 24 1.2 m x 3 m subplots in four randomized blocks, with four replicates of six different treatments. The treatments include urine, side-dressed urine, urine spiked with additional pharmaceuticals, struvite, synthetic fertilizer, and a no-fertilizer control. The side-dressed urine treatment receives the first half of the urine dose at planting time and the second half mid-way through the growth period. The total NPK application rate on each fertilized treatment is 75 pounds/acre of each nutrient, with supplemental synthetic fertilizer being used to achieve P and K application targets in urine-fertilized subplots, and N and K targets in struvite-fertilized plots. To control for the irrigating effect of urine fertilization, water is applied to non-urine-fertilized subplots at the time of fertilization. Soil and plant tissue samples are taken from each subplot at the conclusion of each crop cycle, frozen, and shipped to University of Michigan and University at Buffalo for analysis.

*Figure 3.* Installation of lysimeters to measure pharmaceutical and biological concentrations in soil leachate.

Twenty tank lysimeters buried along one edge of the test plot are used to monitor concentrations of pharmaceuticals and plant nutrients in water leaching through the top 60 cm of soil. Each lysimeter consists of a polyethylene tank equipped with a bottom drain that is connected to a vertical standpipe, through which accumulated water can be removed using a suction wand. The soil column within the lysimeter rests on a rigid permeable floor supported 15 cm above the bottom of each lysimeter, leaving an open reservoir area below the soil column in which leachate can accumulate between sampling events. Standpipes are capped to prevent air exchange between the atmosphere and the reservoir area. To install the lysimeters, a trench was excavated and soil stored in piles corresponding to visually distinct soil layers, the density and depth of which were determined at the time of excavation. The lysimeters were then placed in the trench and packed with soil to recreate the depth and density of the original layers. Water is removed from the lysimeters and sent to Michigan and Buffalo for analysis whenever a sufficient amount accumulates for sampling.

***Agronomic value***:

Since 2012, the Rich Earth Institute has been conducting field trials to quantify the relative effect of sanitized urine fertilizer on hay yields, in comparison with synthetic fertilizer. Results have been encouraging, and the demand for urine fertilizer among participating farmers is currently higher than the available supply.

A major focus of this research has been to test whether yields are affected by diluting urine with water at the time of application. Dilution with three parts water to one part urine is commonly recommended to prevent damage to plant tissues by free ammonia (Richert *et al.* 2010), but the added labor and expense involved in hauling dilution water to the field is a barrier to adoption by farmers.

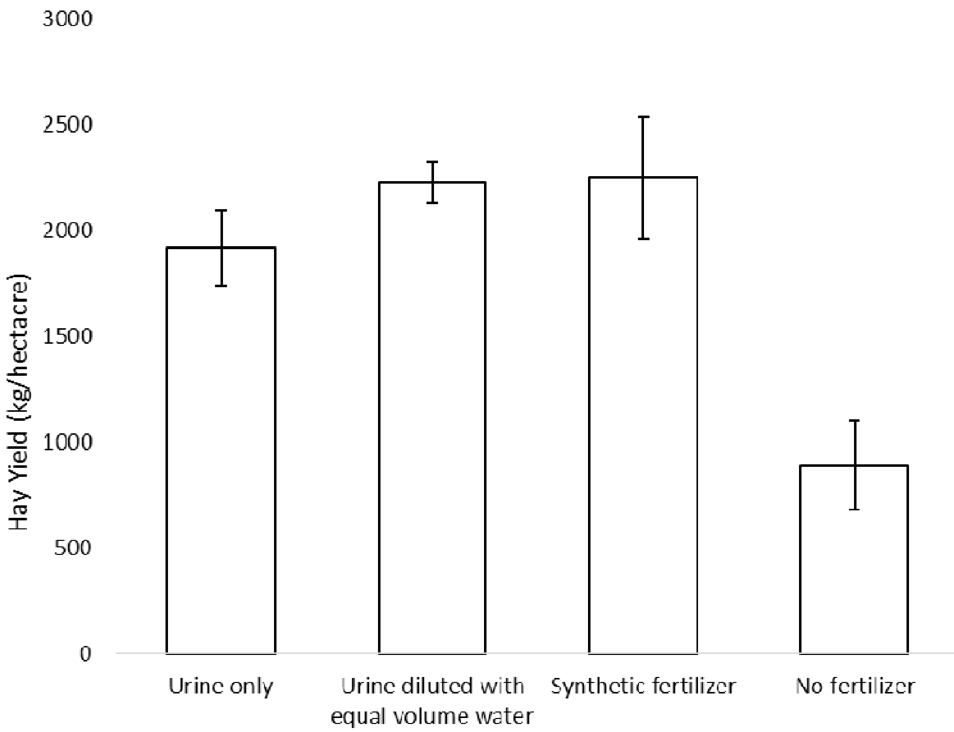
A field trial in 2014 measured the yields of second-cut hay from subplots fertilized with urine, a 50/50 urine/water mix, synthetic fertilizer, and a no-fertilizer control. Subplots measured 5.5 m x 100 m. Urine was applied at a rate of approximately 1000 gallons/acre (1538 L/ha) for an application rate of 50 pounds nitrogen/acre (56 kg/hectare) (Jokela et al. 2004). In addition, the urine provided 7 lbs/acre (7.9 kg/ha) phosphorus and 15 lbs/acre (16.8 kg/ha) potassium. There were three replicates of each treatment, for a total of 12 subplots.

All urine used in the 2014 season was treated through the long-term storage method (>30 days at or above 20°C) in purpose-built, unheated greenhouses made of clear plastic film stretched over wooden frames. Electronic temperature sensors were submerged in the tanks and connected to a datalogger which recorded time-stamped temperature readings for periodic retrieval.

*Figure 4.* On-farm transport and application of sanitized urine.


Urine was applied using a purpose-built urine applicator consisting of a 200-gallon trailer-mounted tank plumbed to a transverse boom with gravity-fed trailing hoses. A remotely actuated valve on the back of the tank allowed the driver to easily initiate or shut off flow when the applicator reached the ends of the study plot. Chemical fertilizer (a blend of urea, triple superphosphate, and potassium chloride) was applied at a rate supplying equivalent NPK as the urine, using a push spreader.

*Figure 5. Effect of urine and synthetic fertilizer application on hay yield*




Results confirmed previous findings (Noe-Hays and Nace 2014) that diluted and undiluted urine are both effective fertilizers, increasing yield in second cut hay. There were no statistically significant differences in yield between plots fertilized with urine, diluted urine, and synthetic fertilizer (Figure 5). Due to the variation in yield between strips within the same treatment, presumably because of the heterogeneous nature of mixed-species perrenial grass stands, further trials with larger or more numerous subplots would be necessary to determine whether the 15% higher yield from the diluted urine treatment compared to the pure urine treatment indicates a true difference or simply an artifact of limited sample size.

**Conclusion**

The Rich Earth Institute is operating the first community-scale urine recycling program in the United States as a means of pursuing its mission: “to advance and promote the use of human waste as a resource.” Investigations conducted to date demonstrate the practicality of urine recycling and are beginning to quantify the real-world economic costs of this approach, while the WERF collaboration provides data regarding the environmental and human health implications. However, this is a young field and much basic research remains to be done. In order to accelerate the expansion of knowledge around urine reuse, the Institute invites other researchers to use its regional program as a test platform for related investigations.

**References**

Calderón-Preciado, D., Renault, Q., Matamoros, V., Cañameras, N., & Maria Bayona, J. (2012). Uptake of Organic Emergent Contaminants in Spath and Lettuce: An In Vitro Experiment. Journal of Agricultural and Food Chemistry, 60(8), 2000-2001.

Fewless, L., Sharvelle, S., Roesner, L., IWA Publishing, Water Environment Research Foundation (2011). Source separation and treatment of anthropogenic urine. Water Environment Research Foundation, London : IWA Publishing, Alexandria, Va

Höglund, C (2001): Evaluation of microbial health risks associated with reuse of source separated human urine, PhD thesis, Royal Institute of Technology, Stockholm, Sweden. ISBN 91-7283-039-5.

Jimenez, J., Bott, C., Love, N. and Bratby, J. (2012) Source Separation of Urine as an Alternative Solution to Nutrient Management in Wastewater Treatment Plants: A Model-Based Analysis. CD-ROM Proceedings of the 85th Annual Water Environment Federation Technical Exposition & Conference, New Orleans, LA.

Jokela, B., Magdoff, F., Bartlett, R., Bosworth, S., Ross, D. (2004). Nutrient Recommendations for Field Crops in Vermont. University of Vermont Extension, Burlington, Vermont

Lienert, J., & Larsen, T. (2007). Soft Paths in Wastewater Management – The Pros and Cons of Urine Source Separation. GAIA - Ecological Perspectives for Science and Society, 16(4), 280-288.

Maurer, M., Pronk, W., & Larsen, T.A. (2006). Treatment processes for source-separated urine. *Water Research, 40*(17), 3151-3166

Noe-Hays, A., & Nace, K. (2014). Sustainable fertilizer from reclaimed urine: A farm-scale demonstration for hay production. Retrieved from http://mysare.sare.org/mySARE/ProjectReport.aspx?do=viewProj&pn=ONE13-188

Richert, A., Gensch, R., Jönsson, H., Stenström, T., & Dagerskog, L. (2010). *Practical Guidance on the Use of Urine in Crop Production* (1st ed.). Stockholm: The Stockholm Environmental Institute.

Udert, K.M. and Wächter, M. (2012) Complete Nutrient Recovery from Source-Separated Urine by Nitrification and Distillation. Water Research, 46, 453-464.

WHO (2006). WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater - Volume IV: Excreta and greywater use in agriculture. World Health Organization (WHO), Geneva, Switzerland

Wysocky, K (2015, May 12) Vermont Pumper Participates in "Peecycling" Study. *Pumper Magazine*