Use of Source-Separated Human Urine to Enrich an Ultisol of the Southern Coastal Plain of the United States

by

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Abstract

Source-separated human urine (SSHU), human urine intentionally diverted and kept separate from feces, has many environmental and agronomical uses. The principal objectives of this research were to investigate SSHU use in composting high C:N ratio oak (*Quercus virginiana*) leaves and in growing collard green (*Brassica oleracea*) for human consumption. Two batches of first morning SSHU were collected from 14 and 20 individuals, inclusively. SSHU was added to oak leaves with high C:N ratio and equilibrated for a long time to facilitate composting. This research demonstrated that SSHU can be diverted from wastewater treatment facilities, significantly decreasing the C:N of oak leaves to improve composting while significantly increasing NO_3-N, P, K, S, Na, Cl^- and pH. Although collard green responded to SSHU, demonstrating that it can be used as a fertilizer, it performed poorly compared to a chemical fertilizer and was harmful at 166 ppm total N level.

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Introduction

Human urine intentionally diverted and kept separate from feces is sometimes referred to as source-separated human urine (SSHU). SSHU management must take into account not only human safety but also soil conditions, plant needs, and practical user concerns.

Managing SSHU for agricultural purposes attempts to harness the positive aspects of its chemical constituents without causing an unacceptable risk or harm from negative aspects of its chemical or microbiological constituents. Potential benefits of SSHU management are not limited to agricultural productivity and human safety, however. For example, SSHU management also presents opportunities for reduced burden on regional wastewater treatment facilities and providing environmental benefits in areas such as the southeastern United States, where septic tanks may cause environmental harm and land disposal of septage is becoming increasingly controversial.

This research is aimed at exploring soil and plant relationships of particular concern to use of SSHU in the Southern Coast Plain of the United States from the vantage point of domestic users of SSHU, who may not be able or willing to store SSHU for long periods of time and who will need careful guidance in order to make efficient and safe use of SSHU to grow plants. The information gained from this research may be useful in developing best management practices (BMPs) for these users.

Source-Separated Human Urine

Nutrients and water the human body cannot store or use are cycled out of the body as waste. The World Health Organization (WHO, 2006) issued guidance for using SSHU as well as other forms of excreta, wastewater, and greywater. This guidance was based mainly on safety concerns. It recommended six month storage of SSHU for use in non-household consumption agriculture but that SSHU can be used without storage on crops for household consumption. The likelihood of household disease transmission from lack of hygiene is much higher than that of transmission through urine used as fertilizer. SSHU use to grow plants for household consumption also may have other advantages including greater knowledge of drug use and medical condition of those contributing the SSHU.

Except for inadvertent contamination with fecal pathogens, SSHU generally reflects the chemical and microbiological composition of urine exiting the urinary system (Lentner, 1981; Putnam, 1971). Urine composition is not stable. Depending upon the length and manner of storage, the chemical composition of SSHU is likely to change, including by conversion of urea to ammonium/ammonia, which in turn increases pH (Kirchmann and Petterson, 1995). Thus storage may be beneficial for its partial sterilizing potential.

Urine contains metabolic byproducts exiting through the urinary system rather than the digestive system. It is normally expected to contain far lower concentrations of pathogenic bacteria (Hall, 2011) and metals (Kirchmann and Petterson, 1995) than feces, which contains both metabolized and unmetabolized compounds. Metal levels in SSHU normally are not expected to present problems for use in agronomic practices and may be lower than some conventional fertilizers.

Urine may contain other chemicals ingested into the human body, including drugs (Hall, 2011; WHO, 2006). Although in a healthy individual urine in the bladder is sterile, simple assumptions of urine sterility can be misleading. During urination, fecal coliform can be picked up by urine. Moreover, fecal contamination of urine is not necessary for it to have safety risk. Bacteria, as well as fungi, parasites, protozoa, and viruses, may be present in the urinary tract.

SSHU use to grow plants is expected to vary by time and place. Some researchers have expressed optimism that SSHU can work well to supply plant needs. Barnard (2009), a leading wastewater treatment engineer, stated SSHU is a complete, well balanced fertilizer with its nutrients readily available to plants. The nitrogen effect has been found to be close to that of chemical fertilizer (~90%), varying between 70% and more than 100%, with the phosphorus effect equal to that of chemical fertilizer (Jönsson et al., 2004).

In addition to providing nutrients and water for plants, terrestrial application of SSHU could provide water quality protection benefits. Alternative methods of treating human waste may discharge constituents that cause environmental problems. SSHU application as fertilizer may be useful in areas with household septic tanks and tile fields that are associated with nuisance ground or surface water problems.

In addition to plant growth enhancement and environmental protection, other factors may affect future SSHU use, including resource scarcity, socio-economics, and cultural taboos (WHO, 2006). Some researchers concerned about long range agriculture supplies of nitrogen and phosphorus have reached the conclusion that a more closed "nutrient loop" should be implemented in humankind's food security interest (Ganrot et al., 2009; Ashley, 2009). Because this loop is involved with the soil, consideration may need to be given to soil interactions by soil scientists assisting in the evaluation and addressing of food security issues (Powlson et al., 2011;

Zhu, 2009; Stocking, 2003). Nutrient depletion in the soil adds to the cost of food production, and extreme depletion can make food production impossible.

Agriculturalists use not only physical but also chemical resources to enhance plant production. These are determined by the earth's chemicals and the availability to the user, just as they are for all living organisms. Developing innovative approaches to material recycling may be a key aspect of improving food security that will involve soil scientists as well as engineers (Zhu, 2009). Improved communication both between disciplines and with the public also may be important.

If SSHU is to play a role in providing food or protecting the environment, it should be carefully studied. SSHU use could be a specific application of practical nutrient management, which takes into account not only the soil but also societal needs and constraints (Brady and Weil, 2008). Soil scientists should be aware of the social context of their work. SSHU use may have potential local niches. Beyond localized needs, practical nutrient management is a matter of global concern.

SSHU use could promote sustainability of food and water supplies. Long range food and water security by definition will require sustainability. Soil fertility is not limited to concern with short term production. Soil scientists have worked to improve not only short term productivity but also the sustainability of soil, agriculture, and the environment (Troeh et al., 2004; Hannam, 2001). Long term inadequacy of global fertilizer supplies could affect both developed and developing countries. Humankind uses a great deal of fertilizer for crop production. Not only food and fiber but also biofuel crops use large amounts of N-fertilizer (Ivanov et al., 2009). The demand for phosphate fertilizer, which cannot be fixed from the atmosphere, also will grow.

In some places, demand already may exist for low or no cost inputs to grow crops, vegetables, and fruit to supplement restricted diets. Smallholder production, with efficiency advantages for labor-intensive products such as vegetables, may be increasingly important. Restricted diets focused on a single food source such as corn meal, which are common among the poor in many developing countries, can be nutritionally inadequate. Micronutrient deficiencies, so-called “hidden hunger,” affect an estimated 2 billion people (Food and Agricultural Organization of the United Nations, 2012a, 2012b). If SSHU may assist some of the world’s poor to have better diets, this would be justification enough for its careful study. The fact that it could also provide potential low cost sanitation, environmental protection, and water conservation benefits also may make SSHU collection and application useful.

Powlson et al. (2011) identified important soil science research issues relating to sustainability, primarily from an environmental protection standpoint but also seeking to maintain or increase food production. For developing countries without full access to affordable fertilizer, they included the need to apply “current knowledge of recycling,” which they suggested would require intermediate levels of research. Soil scientists have evaluated the recycling of nutrients, including those found in animal manures and industrial and municipal byproducts (Brady and Weil, 2008). Troeh et al. (2004) stated that any available sources of organic fertilizer should not be overlooked in a fertility program. They also suggested that available organic sources sometimes may be best applied in combination with inorganic fertilizers.

SSHU Chemistry

Management of SSHU may affect the chemical and microbiological composition of the SSHU itself. Therefore, scientific study aimed at studying the potential use of SSHU for providing crop nutrients may require reliable information pertaining to collection, dilution, and storage. Human urine typically consists of 95-96 percent as water solvent and 4-5 percent as solutes (Lentner, 1981; Putnam, 1971). However, pathogens and foreign substances in SSHU, as well as the distribution of solutes themselves in SSHU, are not necessarily stable.

SSHU instability may in theory be an advantage if changes to SSHU kill pathogens. The chemical composition of fresh SSHU would likely significantly differ from that of SSHU stored for six months or longer (WHO, 2006). The principal anticipated changes during storage involve related phenomena of changes to nitrogen compounds and pH. Due to bacterial activity, the nitrogen compounds would likely change at various stages of storage, affecting pH, while other changes may occur as well (Putnam, 1971).

Stored human urine normally is expected to have a pH slightly higher than stored non-human animal urine (Elmsquist et al., 1997). Upon emission, the pH of human urine ranges from 4.5 to 8.0. With storage, the pH may rise to 9.0, killing harmful pathogens. Fecal coliform bacteria are indicators of fecal contamination of SSHU, which can be addressed through storage (WHO, 2006). Control of pH through SSHU storage, however, is not a panacea. Vinnerås et al. (2008) found that temperature and SSHU dilution rate were important in inactivating bacteria and viruses, with low ammonia concentrations resulting in slow inactivation at temperatures ≤ 24 °C. Higher temperatures combined with high ammonia content could allow the WHO six-month guideline to be shortened.

Interaction with soil, other amendments, and plants may complicate analysis. From a positive standpoint, McKinley et al. (2012) found that the ammonia in stored SSHU combined with ash produced 99% inactivation of ova of *Ascaris lumbricoides*, the giant roundworm of humans, in 8 weeks, with significant inactivation after two weeks. From a negative standpoint, carbamazepine (an anticonvulsant used to treat seizures, nerve pain, and bipolar disorder), but not ibuprofen, was detected by Winker et al. (2010) in both the soil and the roots and aerial plant parts of ryegrass grown with pharmaceutical-spiked SSHU after three months.

Kirchmann and Pettersson (1995) suggested that use of stored, i.e., high-pH, urine for crop nutrients at neutral pH could require lowering of the pH. This could be accomplished by, for example, adding 1 L of concentrated sulfuric acid to the 350 L of urine produced by one individual in a year (Lentner, 1981). However, it is possible that with acidic soils this type of acidifying addition would be unnecessary and that high-pH stored SSHU could at least initially be beneficial for increasing soil pH along with adding nutrients.

Questions also exist concerning the presence and role of urease in rapid conversion of urea to ammonia for stored SSHU. Because rapidly urease-positive *Proteeae* are a diagnostic for urinary tract infections (Jones et al. 1990), one might not expect urease normally to play this role until interaction with the soil, assuming urease contamination in the storage vessel was not present. This may be a moot point if SSHU is directly applied to soil without storage.

Variable by individual, diet, and homeostatic needs, human urine typically has high levels of essential plant macronutrients nitrogen, phosphorus, potassium, and sulfur and micronutrients. It also can contain significant levels of other micronutrients of importance to animals, including iodine and selenium (Lentner, 1981).

90 percent of the human body's waste nitrogen is excreted in urine, with 10 percent excreted in feces (Hall, 2011). At the time of elimination, nitrogenous waste metabolic products are dominated by urea from the metabolism of amino acids but also include creatinine from muscle creatine, uric acid from nucleic acids, and other end products. Protein averages about 16 percent nitrogen. A high protein diet yields large amounts of urea and more concentrated urine, while malnutrition leads to low urea production and urine concentration. The body has an obligatory loss of 20-30 gram/day of protein degraded to amino acids, which are deaminated and oxidized. The ammonia generated through amino acid deamination is converted to urea through the following net reaction:

$$2NH_3 + CO_2 \rightarrow CO(NH_2)_2 + H_2O$$

The typical fresh urine concentration of urea was reported to be 13,400 mg/L in a 1971 study in support of the United States space program (Putnam, 1971). Varying with the amount of protein in the diet, the percentage of N present as urea was reported to range from 50-90 percent in the widely-cited Geigy Scientific Tables (Lentner, 1981), which examined decades of data, some of which may be suspect under modern analytical procedures (Heil et al., 2001).

Urea is not expected to be present in large amounts following prolonged SSHU storage. Soil scientists in Sweden performing a study on SSHU found that concentrations of nitrogen compounds in fresh urine underwent major changes during storage (Kirchmann and Pettersson, 1995). No urea or uric acid was detected in stored urine and only traces of nitrite and nitrate were detected. During storage, urea and uric acid decomposed, with about 95 % of the nitrogen present as ammoniacal nitrogen and the remaining part identified as amino acid-N. This storage effect on nitrogen compounds and pH induce hesitancy in applying scientific studies on stored

SSHU to situations involving fresh SSHU application by household users, who may be among the most likely SSHU users.

Complexity also may arise because of precipitation or other reactions during storage by other analytes, such as phosphate. Calcium, magnesium, and iron can form precipitates with phosphorus in wastewater (Esemen et al., 2009; Hui-Zhen et al., 2009). In addition to complicating study of SSHU, this may have implications on SSHU's efficiency in providing nutrients to plants. Depending on the precipitates formed, storage theoretically could lead to phosphorus being made less available to plants than fresh urine as well as problems of loss due to scale formation in storage vessels.

Nitrogen and phosphorus often must be considered jointly to address plant nutrient imbalances. If adequate levels of available N and P are not present in soil, human life can be rendered precarious in its ability to produce adequate and sustainable supplies of food. On the other hand, over-application of either also may have harmful environmental effects.

Potential benefits and detriments of SSHU ultimately arise from its chemical constituents being applied to soil with its own complex and variable chemical substrate, as mediated by organisms. Hence, as a foundation for practical nutrient management, it may be helpful to have as detailed as possible an understanding of not only SSHU but also the substrate to which SSHU will be applied. Soil and plant interactions of SSHU and other nutrient sources can defy simple expectations. For example, although it is generally assumed that organic nitrogen must first be converted into inorganic nitrogen before plants can benefit, this may not always be the case, particularly for plants with roots having certain mycorrhizal fungi colonies (Sylvia et al., 2005).

Ammonium ions in SSHU would be expected to be enzymatically oxidized by soil bacteria. Nitrification often is portrayed as a simple two-stage process, yielding first nitrite, through *Nitrosomonas*, then rapidly forming nitrate, through *Nitrobacter* (Brady and Weil, 2008). However, autotrophic nitrifiers are physiologically versatile and may be ureolytic, enabling growth with urea as sole nitrogen source (van Elsas et al., 2007). This might be agriculturally significant where fresh SSHU will be directly applied to soils prior to conversion into ammonia/ammonium.

Organic P mineralization also is an enzymatic process mediated by microorganisms (Sylvia et al., 2005). At commonly encountered soil pHs, it will either bind with two hydrogen atoms, as $H_2PO_4^{1-}$ or with one hydrogen, as HPO_4^{2-}, if the pH is 7.2 or greater. Phosphate is a weakly soluble anion that is increasingly unavailable as pH decreases because of binding with Al and Fe.

SSHU Alternatives and Comparisons

The choice of whether to make agricultural use of SSHU is complex and variable. Nonetheless, it may include an overarching binary decision: N, P, and other nutrients contained within excreted human urine may either (1) be used, ideally as efficiently as possible, on land, or (2) disposed, sometimes at great cost in funds and in harm to water and air resources, and potentially unsustainably, as waste on land, in streams, or, in the case of N, also into the air.

When wastewater nutrients are the focus of direct removal efforts through advanced treatment, this typically has been because of heightened concern with eutrophication of water bodies not because of the soil enrichment value of the removed nutrients. Municipal wastewater treatment operations have heavily reflected this environmental protection priority. Much of the phosphorus removed at wastewater plants typically is biologically captured in sludge that is landfilled rather than recycled (California State University [CSU], 2006). Cordell et al. (2009)

estimated that globally 10 percent of human-excreted P was returned to agriculture as sludge or reused wastewater. Moreover, the sludge, also known as biosolids, that is land applied for agricultural or other purposes is increasingly controversial in developed countries based on concerns over pathogens, nutrient overloading of dedicated fields, heavy metal content, and nuisance conditions, including odor (Lu et al., 2012). In comparison, worldwide an estimated 40-50 percent of livestock waste phosphate is recirculated to agriculture (Cordell et al., 2009).

While in theory landfilling at least renders P unlikely to harm the environment, the same degree of relatively permanent stabilization may not exist for N. Much of the N entering wastewater treatment plants is placed in sludge, much of which is landfilled (CSU, 2006). However, with advanced treatment, nitrogen intentionally is wasted to the atmosphere via nitrification-denitrification mediated by bacteria so that it will not get into water bodies beyond permitted limits. This purposely lost N may make a harmful contribution to air pollution, including the greenhouse gas nitrous oxide, N_2O (Law et al., 2012). Townsend-Small et al. (2011) concluded that emissions from wastewater treatment and water reclamation plants in southern California significantly increase nitrous oxide emissions in urban areas. Uncertainty may exist about the specific pathway within a particular advanced wastewater treatment plant primarily responsible for nitrous oxide release to the atmosphere but not that advanced wastewater treatment plants purposely release N to the atmosphere.

By way of comparison to both intentional N losses at wastewater treatment plants and unintentional N losses in agriculture, application of SSHU on bare clay soil and a growing barley crop resulted in low ammonia emissions (Rodhe et al., 2004). It also is possible that if fresh human urine, with a predominance of urea, were applied to soil ammonia losses to the atmosphere would be even lower as urea infiltrates the soil before converting to ammonia. In contrast, risk of nitrate losses from infiltration to groundwater from organic sources of N, including SSHU, may be more comparable to that of mineral fertilizer.

Unlike cattle and poultry manures, SSHU would not currently qualify for use in the U.S. National Organic Program (U.S. Department of Agriculture, 2014). Use of SSHU for soil improvement may be more sustainable and efficient than use of some technically-classified “organic” inputs such as rock phosphate. The latter also may be relatively inefficient in terms of biological availability and have higher trace levels of some unwanted substances (Weinfurtner et al., 2009).

Human urine may have advantages over livestock manures for enriching some soils, including availability to household growers who do not own livestock, and, unlike with livestock manures, the potential to be captured and maintained separate from feces. Some non-human animal waste, including dog and cat manures, are not considered safe for use in growing crops or making compost because these species share many parasites with humans (Kuepper, 2003), this by extension highlighting one of the safety risks associated with SSHU use.

Aside from scientifically-based reasons for caution when using SSHU and other forms of human excreta in agriculture, human excreta has stigma not arising from cattle and poultry manures. Some religious traditions strictly prohibit contact with human excreta (Nawab et al., 2006). However, natural degradation of human excreta from an identifiable mixture into unrecognizable chemical compounds mixed in the soil may allow SSHU use without violating religious prohibitions. SSHU distributed onto soil or socially-acceptable compost material at appropriate quantities may be quicker to lose its separate chemical identity and any associated stigma than combined human waste or feces. In addition, compost production may be a useful consumptive use for excess SSHU during times when SSHU cannot be put to direct use in crop production.

Carbon-rich, nitrogen-poor materials enriched with SSHU should experience a lowering in the C:N ratio. The C:N ratio in untreated leaves is expected to vary somewhat by tree species. Based on data in Wind (2013), the C:N ratio in untreated red oak leaf litter would be expected to be around 68:1. Effective composting is generally expected to require a C:N ratio no higher than 30:1 (Richard and Trautman, 1996). C-related mass loss during the early periods of composting would be expected to be more associated with sugars and starches than with other more complex carbon fractions such as cellulose and lignin (Wind, 2013). Initial SSHU application would be expected to lower the C:N ratio substantially. Thereafter, as C is oxidized during composting, C losses would occur, but so would some N losses, which might be increased with stored SSHU having a high ammonia content.

It should be noted that separation of human urine from feces, because of the potential safety favorability of the urine, to lessen odor formation from the feces, or for other reasons, may not necessarily mean wasting the feces. Under some circumstances human feces could be separately processed to provide organic matter, additional nutrients, or other value, a variation on the conversion by wastewater treatment plants of combined human waste into sludge, some of which is used in agriculture (CSU, 2006). Protecting and enhancing soil organic matter is critical to soil management.

Developing the best local alternatives for soil enrichment is iterative and variable. Inorganic fertilizers often have current comparative advantages over typical organic inputs, including lower transportation costs and higher certainty of N, P, and K content, and these advantages could exist over non-domestic SSHU as well. Nonetheless, scientists have carefully studied various organic materials for adding nutrients to the soil, including such livestock manure sources as dairy cattle, fattening cattle, hogs, horse, sheep, broilers and others. Where cattle or poultry manure is available as a low cost soil input it could provide many of the advantages of SSHU without the stigma and possible higher sanitation risks. However, this may mask long term sustainability problems where cattle and poultry production is heavily dependent on inorganically-grown crops.

Experiences with SSHU in various locales increasingly have been subjected to scientific research. Some sustainable living communities in Europe are engaged in SSHU recovery and thereby facilitate nearby SSHU use in agriculture (Ganrot et al., 2009). Research interest in sustainable alternatives to conventional inorganic fertilizers accelerated after the 2008 world fertilizer price spike. Before that some European researchers had begun to study SSHU. A Swedish study found that the phosphorus in SSHU was significantly more biologically available to plants than inorganic treatment (Kirchmann and Pettersson, 1995).

The Stockholm Environment Institute's (2010) "Practical Guidance on the Use of Urine in Crop Production" specifically focused on SSHU. Projects in many regions of the world outside the United States, including both developing and developed countries, were referenced. An absence of U.S. scholarly interest in SSHU was implied. While the publication does not present a detailed analysis for making use of SSHU in any region, it may be a useful starting point for experiments in other regions that have not been carefully studied for potential SSHU use.

In the U.S., Vermont's Rich Earth Institute, in association with various universities, is undertaking multi-faceted research on SSHU (Noe-Hays et al., 2015), including volume reduction through composting and the presence and persistence of pharmaceuticals in urinederived fertilizers, soils, groundwater, and crop tissues. It found comparable performance in hay production of SSHU to chemical fertilizer even when the SSHU is undiluted and therefore had high ammonia concentration.

Internationally, studies on unadjusted SSHU (e.g., Pradhan et al., 2010; MnKeni et al., 2008; Heinonen-Tanski et al., 2007) and SSHU-compost/SSHU-ash blends (Pradhan et al., 2009) have produced varying crop responses. Pradhan et al. (2010) postulated that adverse SSHU effect on pumpkin yield was due to potassium deficiency and chloride excess. Favorable results were reported in growing cabbage (Pradhan 2007). Growth, biomass, and chloride levels were slightly higher in urine-fertilized cabbage than industrial-fertilized and clearly differed from non-fertilized. Shresthaa et al. (2013) found a better effect on sweet pepper production in Nepal when SSHU was combined with compost. Akpan-Idiok (2012) found a beneficial effect on okra nutrient uptake, growth, and yield from SSHU applied to southeastern Nigerian soil described as mostly loamy sand to sandy loam in texture, acid in reaction, and low in nutrient status.

Research in Ghana with SSHU involved planting multi-year annual crops of sorghum in an arid location (Germer et al., 2011). The study included partially supplementing urine treatments with P and K inorganic fertilizer to have comparable levels of macronutrients to the conventionally fertilized plots. Combining of this inorganically supplemented SSHU with compost (maize and sorghum straw) also was evaluated and produced the highest yield. The adjusted SSHU and compost treatments raised pH and cation contents of the upper 0-15 cm, while pH and cation contents in this layer were lowered with inorganic fertilizer treatments.

Andersson et al. (2013) found a significant positive effect from the N in SSHU on maize in South Africa in a study focused on rain fed smallholder farming. An earlier maize study in Zimbabwe also found significant positive effects from SSHU, surpassing inorganic fertilizer

(Guzha, 2005). This study found that combining SSHU with separately-treated feces produced even more favorable results.

In some places ordinary people have taken a keen interest in SSHU collection and use. Some agriculturalists, however, may not focus on sustainability issues. Apathy toward SSHU as a potential nutrient source for enriching soil in a particular area may not be overcome with science alone. Nevertheless, stigma and potential regulatory barriers to SSHU could persist for which scientific research could be beneficial. Over time, with appropriate research, BMPs could be developed for efficiently and safely using SSHU to grow plants.

From a long term standpoint, the Southern Coastal Plain of the United States has major metropolitan areas that at some point theoretically could be expensively retrofitted to facilitate SSHU use. More realistically, it has many military bases and installations, universities, colleges, airports, factories, prisons, and other major rural or peri-urban institutions that could provide large scale sources of SSHU for nearby non-household agriculture. Soil and plants could divert from the waste stream and make beneficial use of SSHU, which also could be processed for N and P for non-agricultural applications. Because the U.S. military already is moving in the direction of waterless toilet technology for water and energy savings and to minimize expensive wastewater treatment (Stumpf, 2007), SSHU collection and use would seem a potentially good long term fit for military bases and installations undergoing construction or retrofitting.

In the immediate time frame, the Southern Coastal Plain also has significant levels of persons living in poverty, including many female-headed families living in rural areas (Zekeri, 2007). Some of those living in poverty theoretically could benefit even in the near term from the free but hitherto unrealized availability of SSHU to enrich soil to grow healthy food. Yet this possibility could encounter not only typical levels of stigma but also serious resentment. In an era of great inequality, any selective suggestion that less advantaged members of society should start growing some of their own food using SSHU may not be well-received.

A more egalitarian approach might be to focus potential SSHU use in the Southern Coastal Plain on society more generally. Residents who are connected to municipal utilities might be able to reduce their water and sewer bills through SSHU collection and use. Each instance of SSHU collection and use could be an avoided toilet flush and a resulting water savings.

Similarly, a major opportunity for SSHU use in the Southern Coastal Plain may involve the gradual technological replacement of septic tanks and tile fields with a SSHU-based alternative. If a practical SSHU-based alternative to septic tanks and tile fields were available in the Southern Coastal Plain this could in some places alleviate existing environmental and health threats. Septic tanks eventually need to be replaced. SSHU-based technology possibly could be implemented to turn this replacement into a societal advancement. The status quo may be less fixed in some areas within developing countries, where less funds may have been or be available for traditional "Western plumbing" and expensive regional wastewater treatment systems.

Land application of septage from septic tanks, like land application of biosolids from wastewater treatment plants (Lu et al., 2012), is becoming increasingly controversial in developed countries (Harrison and Moffe, 2003), including in the southeastern U.S. (Pittman, 2011). Florida portions of the Southern Coastal Plain may be subject to a prohibition on land application of septage from onsite treatment and disposal systems effective January 1, 2016 (FLA. STAT. § 381.0065(6) (2018)). In part because of water basin connections to Alabama and Georgia, states to the north within the Southern Coastal Plain, pressure may increase for them to adopt similar restrictions.

If SSHU collection and use, in combination with acceptable management of feces, can be implemented in relatively inexpensive, water-conservative, environmentally advantageous, and, most importantly, safe ways, this might provide an alternative to the current usage of septic tanks, tile fields, and land application of septage in some of the area. Thus, demand may develop for a SSHU-based alternative in the Southern Coastal Plain. Society may be well-served if soil scientists are prepared to advise households and other potential users about the key soil interactions of SSHU with regional soils.

With the potential opportunity to fill a niche for residents in the Southern Coastal Plain who may wish to avoid or replace septic tanks and tile fields with a SSHU-based alternative would come a responsibility to assure continuous usage of the available SSHU. In addition, some potential household users of SSHU may be uninterested in storing SSHU for prolonged periods prior to use. Some potential users may be able to use excess SSHU for composting with readily-available organic materials.

It may also be desirable for SSHU to be usable directly in the soil year-round for growing plants that are of value to the user. For some, it might do little practical good for the environment or public safety if SSHU could only be productively put to use growing long season plants. This raises the question of whether short season plants suitable to the Southern Coastal Plain can be productively grown using SSHU during the winter.

Objectives

The objectives of this research were (1) to provide basic information on SSHU, and in particular, to study short-term changes in NH_4-N, NO_3-N and soil pH in SSHU-treated soil; (2) to evaluate SSHU use in rapidly composting oak leaves, a commonly-available high C:N material; and (3) to evaluate SSHU use in growing a short season plant, specifically collard green (*Brassica oleracea*), on an Ultisol soil (Benndale, coarse-loamy, silicious, semiactive, thermic, Typic Paleudults), an important soil in the southeastern United States.

Materials and Methods

SSHU and Soil Collection and Analysis

For the first part of the research, a total of 840 mL of SSHU was collected. Sixty mL of SSHU were obtained from each of 14 individual donors who had provided informed consent. SSHU for the greenhouse study was collected from 20 donors, each giving 60 mL of SSHU following the same procedure as with the first batch, for a total of 1200 mL of SSHU collected in the second batch. The donors were instructed to collect the SSHU on a particular day with their first morning urination into sterile containers, which were then placed within brown bags to preserve anonymity. The collected SSHU was then combined and mixed within a 5-gallon vacuum-top-locked container. SSHU not immediately used was stored in an enclosed shed without temperature control, experiencing a range of temperatures consistent with Plant Hardiness Zone 8b (U.S. Department of Agriculture, 2012).

To compare chemical concentrations between SSHU collection events, for each SSHU batch a sample of the applicable combined SSHU was analyzed by a commercial laboratory (TestAmerica, Pensacola, FL) for bromide, nitrate-N, chloride, nitrite-N, fluoride, orthophosphate as P, sulfate, and total sulfur using USEPA Method 9056; for total recoverable potassium using USEPA Method 6010C; and for total Kjeldahl nitrogen, total phosphorus, ammonia-N, and pH using general chemistry. Prior to chemical analysis, the first and second batches of SSHU were stored in the enclosed shed four months (February 2017-June 2017) and twelve months (April 2017-April 2018), respectively.

90 kg of Benndale soil was obtained from Auburn University's Brewton Agricultural Research Unit in Brewton, Alabama, from an uncultivated grassy field. The top six inches of the soil was sampled, screened, and air dried. Three samples were sent to the Auburn University Soil Testing lab in Auburn, Alabama. The following analyses were performed.

pH

Ten cm^3 of soil was mixed with 10 mL of water and equilibrated for 30 minutes. The pH of the solution was measured with an AS-3000 Dual pH meter, after appropriate calibrations. A buffer pH was determined after adding 10 cm^3 of modified Adam's Evans buffer solution to the soil-water solution (Huluka, 2005). This resulted in a 1:1:1 soil:water:buffer ratio.

Elemental Analysis

Five g of soil sample was weighed and added to an Erlenmeyer flask. Twenty mL of Mehlich I solution was added, and samples were then shaken for 5 minutes. After filtering, the solution was analyzed for P, K, Mg, Ca, Zn, Mn, and others by inductively coupled plasma (ICP).

Carbon by Dry Combustion

Carbon was measured using Elementar vario Macro CNS analyzer (Mt. Laurel, NJ) by burning 0.16 to 0.20 g of soil sample at 960°C in pure O_2 gas. The result from dry combustion was reported as total soil carbon and N.

ECEC

Effective cation exchange capacity (ECEC) was calculated based on a summation of K, Mg, and Ca extracted by Mehlich-1 and the exchange acidity using modified Adams-Evans buffer (Huluka, 2005).

The calculations were made using the following equations:

$$\text{Extractable } Ca^{2+} \text{ (cmolc/kg)} = \text{Mehlich-1 Ca (lb/A)}/400.8$$

$$\text{Extractable } Mg^{2+} \text{ (cmolc/kg)} = \text{Mehlich-1 Mg (lb/A)}/243$$

$$\text{Extractable } K^{+} \text{ (cmolc/kg)} = \text{Mehlich-1 K (lb/A)}/782$$

Base Saturation

Base saturation (BS) percentage was calculated based on the ECEC. The sum of bases was divided by ECEC. This number was then multiplied by 100.

Soil Incubation with SSHU

In the SSHU-treated soil laboratory study, 22 mL of SSHU (47 mg/kg N) was added to 3 kg of soil moist to field capacity. A soil sample was extracted with distilled water and NO_3-N, NH_4-N and pH were measured at the following intervals after SSHU application: 12 hours, 24 hours, 2 days, 3 days, 4 days, 5 days, 6 days, 7 days, and 10 days.

Oak Leaf Compost Collection and Treatment with SSHU

For the compost study, 200 g of southern live oak (*Quercus virginiana*) leaves were collected. The leaves were unwashed brown leaves collected from the natural ground surface so that it would be unnecessary to add a soil inoculum to introduce soil microbes.

The leaves were divided into two 100 g portions which were then ground by blender using distilled water as necessary to provide a lubricant and create a slurry, then placed in separate open-topped 1000 mL glass beakers. One beaker was treated with SSHU, and the other beaker received equivalent volumes of additional distilled water. Additional distilled water was also regularly applied to and stirred within each beaker to maintain damp but unsaturated composting conditions. The treated and untreated beakers of ground oak leaves were cured under identical low intensity heating lamps for 21 days, with regular rotation between lamps as much as practicable to assure equal exposure to each lamp. The heating lamps were intended to compensate for the small volume. After 24 hours the material in each beaker reached and typically remained around 38 ºC, which provided substantial heating in comparison to ambient indoor temperature but not enough to fully simulate rapid composting conditions of 65 ºC.

At the beginning of the compost curing period, and after 8 and 14 days of composting, 181, 91, and 91 mL, respectively, of SSHU or additional distilled water were added into the appropriate beaker, which was then stirred. The volume of SSHU added to the treated oak leaves was intended to approximate an optimum C:N ratio for rapidly composting oak leaves. For maximizing the rate of composting, it was assumed to be desirable to achieve a target ratio of 20:1 with the initial SSHU application and to use subsequent applications at days 8 and 14 to replace N possibly lost through volatilization, for a total N addition from SSHU of 3% of the initial mass of oak leaves.

During the composting period, the contents of each beaker were periodically photographed under microscope to assist in documenting visual differences. After the 21-day composting period, the contents of each beaker of compost were allowed to air dry for a 24-hour period and again photographed under microscope. Then the composts were each placed in separate plastic sealed bags. After fifteen months, the composts, by then completely dry, were unsealed and once again observed and photographed under microscope. A sample was extracted with distilled water and analyzed for nitrate, chloride, and pH. In addition, three months later ground samples of raw oak leaves, untreated oak leaf compost, and SSHU-treated oak leaf compost were analyzed by the Auburn University Soil Testing lab for C, N, P, K, S, Na, pH and other parameters.

Greenhouse Study

Three kg soil samples were placed into pots with open drainage holes and leachate collection plates. A randomized block design was used with four blocks, each block having all seven treatments present for a total of 28 mature plants, each in a separate pot. SSHU used in the greenhouse study had been stored for a minimum of four months. Either the appropriate volume of SSHU based on measured-N from the first SSHU batch or Miracle-Gro® (24-8-16) (M-G) with 0, 30, 60, and 120 ppm N were added to soil samples, with no extra additions of P or K to SSHU. The treatments were divided into three equal 50 mL portions, the first applied 53 days prior to seeding, the second 37 days after seeding, and the last 79 days after the second. SSHU was diluted with distilled water to provide the estimated total N level in accordance with the following proportions: 30 ppm—4.7 mL SSHU + 45.3 mL H_2O; 60 ppm—9.4 mL SSHU + 40.6 mL H_2O; 120 ppm—18.8 mL SSHU + 31.2 mL H_2O.

The plant experiment was conducted in a 12'L x 7'4" W x 7'5" greenhouse equipped with an axial fan and digital environmental controller system capable of providing limited cooling and preventing excess humidity. As the plant experiment was designed to use a cool season plant grown during the winter, the lack of warm weather cooling capability was not expected to cause a problem for normal plant growth. Manual watering was supplemented by passive drip water devices in each pot.

Because the stored SSHU also was expected to have a high pH, caution was used to protect the collard green seeds and seedlings. For the fall collard green planting, 50 days prior to sowing the initial SSHU and fertilizer treatments were applied to the soil. A comparable amount of distilled water was applied to the untreated pots. After the curing period, cooler weather conditions favorable for collard green growth had arrived. Three collard green seeds were sowed ½” deep in trigonal fashion near the center of each pot, with the seeds and soil watered using distilled water. Each pot had at least one successful seedling, and thinning occurred to one plant per pot within three weeks of sowing.

Statistical Analysis

RStudio (Version 1.1.453, 2016) was used for data analysis. Linear regression modeling was used to determine statistically significant differences at ≤ 0.05 and ≤ 0.01 levels of probability. Linear mixed effects modeling was also used to determine if mixed effects usage improved statistical validity. In addition, two sample t tests for unequal variance were used on the greenhouse plant response and residual chemicals.

Results

Analysis of the Benndale soil showed that the apparently natural soil at this specific location was generally rich in plant macronutrients and micronutrients, with no appreciable potentially harmful heavy metals (Appendix I). The sample field has been under pasture for many years, and only the top six inches was sampled. The soil has relatively high organic matter. % C and % OM of 3.28 and 5.6, respectively, were found, with pH and buffer pH of 5.50 and 7.57, respectively. The OM value was calculated from OC using a 1.71 factor. N, P, K, Ca, and Mg ppm levels were 2700, 18, 72, and 104, respectively, with ECEC of 10.3 Cmolc/kg. The C:N ratio for this soil was 12:1 as expected.

Results of the commercial lab testing of the two SSHU batches of first morning SSHU are shown in Table 1. The second batch had a higher total N concentration and other differences from the first batch unrelated to length and conditions of storage prior to testing. Variation based on time of day that SSHU is voided was minimized by collecting first morning SSHU, which may be more easily collected for domestic use by some individuals than after involvement in activities away from residences. Nonetheless, this temporal restriction and batch collection from relatively large groups of people as opposed a single person or family did not eliminate differences between batches. As an added word of caution, the data does not identify microbiological organisms or all chemicals that may be present in SSHU, including pharmaceuticals.

Short-term SSHU Soil Incubation

Nitrogen present in SSHU will undergo chemical changes when it leaves the body, including when it is applied directly to the soil without prolonged storage. Results of the laboratory study of 3-kg of fresh SSHU-treated soil in the first part of the research are shown in Table 2. This examined shifts from urea to ammonium to nitrate over a 10-day period. The initial analyses revealed some ammonium and nitrate levels naturally present in the soil. The data overall revealed expected shifts as urea, the dominant nitrogen compound naturally present in SSHU when it is first emitted from the body, was broken down in microbiologically-mediated processes to ammonium and eventually to nitrate.

Oak Leaf Compost Study

Based on the first batch of SSHU, the total N addition to the 100 g of oak leaves was actually 2.3 g, i.e. 2.3% of the initial mass of oak leaves. Comparison of the treated and untreated oak leaf composts was part qualitative and part quantitative.

During the compost experiment, a persistent pungent aroma was present with the SSHU-treated compost that was not present with the untreated compost, and a far darker and richer color was associated with the SSHU-treated compost. Photography of differences observed during and one day after the 21-day simulated rapid composting experiment is presented in Figure 1. Fifteen months later, the pungent aroma of the SSHU-treated compost was substantially diminished, but the fully dry composts continued to be quite distinct visually, with the SSHU-treated compost now having a dark gray ashy appearance, as depicted in Figure 2.

Residual nitrate, chloride, and pH data associated with the treatment of oak leaves with SSHU after fifteen months of curing is presented in Table 3. Statistically significant differences between treated and untreated compost were found for residual levels of nitrate, chloride, and pH. Applying SSHU at a rate of 2.3% for each 100 g of oak leaves raised residual nitrate concentration 39 mg/kg, residual chloride concentration 2222 mg/kg, and pH 1.12. (See Table 4 for statistically significant linear regression model parameter estimates of SSHU and M-G effects.)

Analysis of the raw oak leaves, untreated leaf compost and SSHU-treated oak compost for C, N, C:N ratio, P, K, S, Ca, Mg, Na, and pH three months later is shown in Table 5. The raw oak leaves used in the experiment had a comparable N content to the one reported by Wind (2013), but a much higher C content and consequently a much higher C:N ratio than anticipated. The 1.15 g of N from SSHU actually applied at the start of the composting experiment corresponded to a 87:1 C:N ratio, much higher than the target ratio of 20:1. But, when combined with boosters of 0.58 g N at days 8 and 14 (for a total N addition of 2.3 g), a major lowering effect on C:N occurred. Composting without SSHU reduced the C:N ratio by 17% from raw oak leaves, but composting with SSHU reduced the C:N ratio much more dramatically, by 70%, meaning that composting with SSHU was more than 4 times as effective at lowering C:N ratio.

Both mass effects and chemical reactions were involved in this shift. The SSHU treatment resulted in a 3.7% decrease of the percentage of C present. However, much of the downward shift in C:N came from the mass effect from the N additions present in the SSHU rather than increased C oxidation. 85% of the N remained in the SSHU-treated compost. Conversely, although N volatilization was not the focus of the experiment, the total N in the SSHU-treated compost of 3.14% decreased to 2.68 % eighteen months after the experiment had concluded, for a net N loss of 15%. Differences were also observed with P, K, S, and Na, which unlike N do not volatilize under normal conditions. Each substantially increased with SSHU treatment.

Greenhouse Study

Table 6 presents mean collard green biomass and stem height in response to N treatments with SSHU and M-G, and mean residual soil Cl^-, K, NO_3-N, P, Ca, Mg, and Na. Because the second batch of SSHU, which had higher total N than the first batch, was used in the greenhouse study, the SSHU treatments in the greenhouse study actually applied 0, 41, 83, and 166 ppm total N rather than 0, 30, 60, and 120 ppm total N. Treatment with M-G yielded significantly greater biomass than SSHU ($P:\leq 0.05$) even though the SSHU treatment using the second SSHU batch had higher N.

No or minimal positive effects from SSHU use were seen at low and moderate levels, with striking negative effects at high level (Figure 3). M-G use showed the expected relatively linear increase up to the recommended moderate level of 60 mg/kg, with a decrease in biomass at excess level but still positive effect in comparison to control. When the M-G application was no higher than the recommended level, an additional 0.23 g of collard green biomass was produced with each additional mg/kg of N.

Based on post-treatment soil testing, residual concentrations of several chemicals associated with treatment with SSHU or M-G could be agronomically important. However, only sodium was found to be present at significantly higher comparable levels when SSHU was used rather than M-G. Residual sodium increased an additional 19 mg/kg when SSHU was used rather than M-G. Residual nitrate, chloride, potassium, and sodium remained at significantly higher levels over the untreated soil regardless of whether SSHU or M-G was used. Residual nitrate and potassium increased 0.75 mg/kg and 0.42 mg/kg, respectively, for each mg/kg of N associated with SSHU or M-G treatment, while residual sodium and chloride increased 0.31 mg/kg and 0.07 mg/kg, respectively.

Discussion

The Ultisol that was used for this research was generally fertile. However, for growing vegetables such as collard green, Auburn University's Soil Testing lab recommended additions of N-P-K 120-60-120 pounds/acre, i.e. 60-30-60 mg/kg, as well as 1.5 tons/acre limestone to address acidity. Collard green needs ample nitrogen for a cool season plant (Sanders, 2001).

The medium level SSHU treatment, 83 mg/kg, should have readily provided adequate nitrogen for plant needs, assuming it did not volatilize prior to plant use. Absent loss to the atmosphere, whether fresh SSHU with a high concentration of urea is used or long-time stored SSHU with a high concentration of ammonium/ammonia, the nitrogen compound applied to the soil should within a week to ten days substantially convert to readily available nitrate. In addition, in theory high pH stored SSHU could have the added advantage of providing some base to acidic soil such as this Ultisol. However, the high pH associated with long-term storage may also contribute to volatilization of ammonia or be associated with high ammonia that could adversely affect plants.

Furthermore, achieving the recommended level of phosphorus and potassium with SSHU alone may not be possible without over-applying SSHU based on total N requirement. SSHU is not the perfectly balanced nutrient source some proponents assume. Mean K was three times higher than mean P in the SSHU batches and may not have been a factor in poor performance. However, mean P in the SSHU batches was less than ten percent of mean N. Because of the potential for P and K deficiency from use of SSHU alone, supplementing SSHU with P and K from extraneous sources may be necessary.

In contrast to P and K deficiency, SSHU could lead to excess salt in the soil solution from sodium and chloride. High concentrations of sodium and chloride may reduce growth rate, harm roots, and “scorch” leaves (Shannon and Grieve, 1999), phenomena observed in the collard green plants treated with SSHU at 166 ppm total N level. If undiluted, the sodium levels in SSHU alone would be several times the 1000 ppm upper salt limit normally recommended for growing plants (University of Florida, n.d.), too high even for a plant such as collard green expected to have relatively high salt tolerance. The SSHU dilution to 38% strength associated with the 166 ppm total N treatment was still applying sodium at over three times the 1000 ppm amount.

Comparing the collard green study’s residual soil sodium concentration to the sodium concentration found in the compost study similarly evidences potential for the soil solution to be adversely impacted. Both SSHU-treated soil and SSHU-treated compost showed sodium accumulation with SSHU treatment, but as seen in Tables 5 and 6, the compost sodium level was 78 times higher than the residual soil level. The compost study suggests that high chloride also could become an issue for the soil solution, although the residual soil data did not show a statistically significant difference from commercial fertilizer.

Electrical conductivity, which was not analyzed, is the usual measure for salinity (Shannon and Grieve, 1999). Whether salinity or sodium levels in SSHU would adversely affect the soil in the long run might vary by climate. Sodium Adsorption Ratio (SAR) is a widely used index for examining soil sodicity (Sonon et al., 2012). It characterizes soil as sodic if it exceeds 13 using the following formula:

$$\text{SAR} = [\text{Na concentration}]/\sqrt{1/2([\text{Ca concentration}] + (\text{Mg concentration}])}$$

SAR calculation requires methods not used in this research, but it is possible that if SSHU is regularly applied to soil SAR would rise. Although it seems doubtful that in a high rainfall area the sodic level would be reached, excess sodium likely was taken into the plants, where it apparently caused great harm. Without plants to absorb the sodium, it could remain in the soil until leached into the groundwater by rainfall. Focusing solely on soil residual concentrations could cause a false sense of security when in actuality plants may be absorbing excess levels of sodium and chloride.

It is not known definitively what factor or combination of factors caused the poor relative performance of SSHU in the greenhouse study. It is possible that by selecting first morning SSHU the collection design was unfavorable when compared to the SSHU used in other studies producing better plant response. However, because domestic users could by choice or necessity apply first morning SSHU to the soil, this relative disadvantage may be indicative of a practical concern. Exposing risks or shortcomings of SSHU may be as worthwhile as publicizing its advantageous qualities. By having a fuller practical perspective on SSHU, the development of BMPs for SSHU use may be encouraged. In addition, better understanding SSHU's limitations can ensure that the need for supplementation with other chemical resources remains a central focus.

Compost may present a useful material for managing helpful or harmful effects of SSHU application. The possibility that compost could be treated with SSHU and, through microbiological activity, turn useful chemicals into organic material may need to be carefully studied. Of particular interest may be to see if this also could facilitate preferential leaching of sodium or preferential leaching or volatilization of chloride. Alternatively, plants suitable for growing in, and potentially absorbing, high levels of sodium and chloride may need to be a focus of study. Even if the sodium and chloride in SSHU-treated compost ultimately may present difficulties for long-term agronomical use, SSHU use in composting may be valuable in some settings for environmental protection or landfill management reasons.

Conclusion

Humans long have been making use of available substances such as animal excreta to grow plants. Although learning whether and how best to use SSHU likely will vary by setting, regional BMPs for SSHU use could be developed to assist the public and policy-makers. The future may present challenges and opportunities for SSHU use not widely recognized today. SSHU management could become an important part of environmental and agronomical planning.

In rural and urban areas, scientists and engineers are being called upon to address ground and surface water pollution from nutrients and pharmaceuticals. In addition, some individuals on regional wastewater treatment systems may wish to collect SSHU to cut down on flushing. In rural areas, including portions of the Southern Coastal Plain of the United States, septage disposal is becoming controversial even where septic tanks and tile fields may not be causing pollution problems. Addressing some of these challenges may be more feasible with SSHU, compost, and soil systems than with combined wastewater flows.

SSHU presents practical challenges both to study and to efficiently and safely use. Mistakes and successes in controlled settings may illustrate and better inform SSHU use but not fully reflect difficulties that would be faced through widespread SSHU collection. SSHU is odoriferous, high in volume per unit of nutrient, decentralized in collection, chemically and microbiologically variable, and salty, factors that could be daunting as crop inputs for farmers.

Particular attention may need to be focused on composting in SSHU management. SSHU-treated compost presents a useful material for managing some positive and negative aspects of SSHU. SSHU composting could turn otherwise wasted or harmful chemicals into useful organic material while decreasing the amount of high C:N material transported to landfills, ameliorating high ammonia that could harm some plants through direct SSHU application, and reducing volume. However, the potential for high sodium and chloride in SSHU-treated compost would need to be addressed as part of SSHU management, considering such factors such as soil conditions, plant salinity tolerance, and rainfall.

References

Akpan-Idiok, A.U., I.A. Udo, E.I. Braide, E.I. 2012. The use of human urine as an organic fertilizer in the production of okra (*Abelmoschus esculentus*) in South Eastern Nigeria. Resour., Conserv. Recycl. 62:14– 20.

Andersson, J., A. Zehnder, B. Wehrli, G. Jewitt, K. Abbaspour, H. Yang. 2013. Improving crop yield and water productivity by ecological sanitation and water harvesting in South Africa. Environ. Sci. Technol. 47:4341−4348.

Ashley, K. 2009. Preface. International Conference on Nutrient Recovery from Wastewater Streams. IWA Publishing, London, UK.

Barnard, J.L. 2009. Elimination of eutrophication through resource recovery. International Conference on Nutrient Recovery from Wastewater Streams. IWA Publishing, London, UK.

Brady, N.C., R.R. Weil. 2008. The nature and properties of soils, 14th ed. rev. Prentice Hall, Upper Saddle River, NJ.

California State University, Sacramento, Office of Water Programs. 2006. Advanced waste treatment: A field study training program, 5th ed. OWP, CSU, Sacramento, CA.

Cordell, D., T. Schmid-Neset, S. White, J.-O. Drangert. 2009. Preferred future phosphorus scenarios: A framework for meeting long-term phosphorus needs for global food demand. International Conference on Nutrient Recovery from Wastewater Streams. IWA Publishing, London, UK.

Elmsquist H., L. Rodhe, M. Blomberg, S. Steineck, B. Lindén. 1997. Human urine and effluents from digestion of food refuse as a fertiliser to barley – crop yields, ammonia emission and nitrate leakage [Online]. Available at http://ramiran.uvlf.sk/doc98/FIN-POST/ELMQUIST.pdf (verified 12 Nov. 2018). Swedish Institute of Agricultural Engineering, Uppsala, Sweden.

Esemen, T., W. Rand, T. Dockhorn, N. Dichtl. 2009. Increasing cost efficiency of struvite precipitation by using alternative precipitants and P-remobilization from sewage sludge. International Conference on Nutrient Recovery from Wastewater Streams. IWA Publishing, London, UK.

FLA. STAT. § 381.0065(6) (2018).

Food and Agricultural Organization of the United Nations, 2012a. FAO statistical yearbook 2012: World food and agriculture [Online]. Available at http://www.fao.org/docrep/015/i2490e/i2490e00.htm (verified 12 Nov. 2018). FAO, Rome, Italy.

Food and Agricultural Organization of the United Nations, 2012b. The state of food insecurity in the world: Economic growth is necessary but not sufficient to accelerate reduction of hunger and malnutrition [Online]. Available at http://www.fao.org/docrep/016/i3027e/i3027e00.htm (verified 12 Nov. 2018). FAO, Rome, Italy.

Ganrot, Z., J. Broberg, S. Byden. 2009. Energy efficient nutrient recovery from household wastewater using struvite precipitation and zeolite adsorption techniques: A pilot plant study in Sweden. International Conference on Nutrient Recovery from Wastewater Streams. IWA Publishing, London, UK.

Germer, J., S. Addai, J. Sauerborn. 2011. Response of grain sorghum to fertilisation with human urine. Field Crop Res. 122 (2011) 234-241.

Guzha, E., I. Nhapi, J. Rockstrom, J. 2005. An assessment of the effect of human faeces and urine on maize production and water productivity. Physics and Chemistry of the Earth 30:840–45.

Hall, J.E. 2011. Guyton and Hall textbook of medical physiology, 12th ed. Saunders, Elsevier Inc., London, UK.

Hannam, I. 2001. Ecologically sustainable soil: The role of environmental policy and legislation. Sustaining the global farm. 10th Inter. Soil Conservation Organization Meeting, pp. 95-100 [Online]. Available at http://topsoil.nserl.purdue.edu/nserlweb-old/isco99/pdf/ISCOdisc/SustainingTheGlobalFarm/P010-Hannam.pdf (verified 12 Nov. 2018). Purdue Univ., West Lafayette, IN.

Harrison, E.Z., M. Moffe. 2003. Septage quality and its effect on field life for land applications. J. Am. Water Resour. Assoc. 39(1):87-97.

Heil, W., J. Edelmann, W. Kiemstedt, B. Zawta. 2001. Reference ranges for analytes in extravascular body fluids. Clin. Lab. 47(1-2):7-16.

Heinonen-Tanski, H., A. Sjöblom, H. Fabritius, P. Karinen. 2007. Pure human urine is a good fertilizer for cucumbers. Bioresour. Technol. 98:214-217.

Huluka, G. 2005. A modification to the Adams-Evans soil buffer determination solution. Commun. Soil Sci. Plant Anal. 36(15-16):2005-2014.

Hui-Zhen, W., Z. Ya-jun, F. Cui-Min, X. Ping, W. Shao-Gui. 2009. Study on phosphorus recovery by calcium phosphate precipitation from wastewater treatment plants. International Conference on Nutrient Recovery from Wastewater Streams. IWA Publishing, London, UK.

Ivanov, V., C.H. Guo, S.L. Kuang, V. Stabnikov. 2009. Phosphorous recovery and nitrogen removal from wastewater using BioIronTech process. International Conference on Nutrient Recovery from Wastewater Streams. IWA Publishing, London, UK.

Jones, B.D., C.V. Lockatell, D.E. Johnson, J.W. Warren, H.L.T. Mobley. 1990. Construction of a urease-negative mutant of *Proteus mirabilis*: Analysis of virulence in a mouse model of ascending urinary tract infection. Infect. Immun. 58(4).

Jönsson, H., A.R. Stintzing, B. Vinnerås, E. Salomon. 2004. Guidelines on the use of urine and faeces in crop production. EcoSanRes Publications Series. Report 2004-2 [Online]. Available at http://www.ecosanres.org/pdf_files/ESR_Publications_2004/ESR2web.pdf (verified 12 Nov. 2018). Stockholm, Sweden.

Kirchmann, H., S. Pettersson. 1995. Human urine – Chemical composition and fertilizer use efficiency. Fert. Res. 40:149-154.

Kuepper, G. 2003. Manures for organic crop production [Online]. Available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.474.205&rep=rep1&type=pdf (verified 12 Nov. 2018). ATTRA, National Center for Appropriate Technology, Fayetteville, AR.

Law, Y., L. Ye, Y. Pan, Z. Yuan. 2012. Nitrous oxide emissions from wastewater treatment processes. Philos. Trans. R. Soc., B 367(1593):1265-77.

Lentner, C. (ed.). 1981. Geigy scientific tables vol. 1: Units of measurement, body fluids, composition of the body, nutrition, 8th ed., rev. Ciba Geigy Limited, Basel, Switzerland.

Lu, Q., Z. He, P. Stoffella. 2012. Land application of biosolids in the USA: A review. Appl. Environ. Soil Sci. 2012: ID 201462.

McKinley, J.W., R.E. Parzen, Á.M. Guzmán, J. McMurry. 2012. Ammonia inactivation of *Ascaris* ova in ecological compost by using urine and ash. Appl. Environ. Microbiol. 78(15):5133-5137.

MnKeni, P., F. Kutu, P. Muchaonyerwa, L. Austin. 2008. Evaluation of human urine as a source of nutrients for selected vegetables and maize under tunnel house conditions in the Eastern Cape, South Africa. Waste Manage. Res. 26:132-9.

Nawab, B., I.L.P. Nyborg, K.B. Esser, P.D. Jenssen. 2006. Cultural preferences in designing ecological sanitation systems in North West Frontier Province, Pakistan. J. Environ. Psychol. 26:236-246.

Noe-Hays, A., K. Nace, N. Patel, R. Lahr, H. Goetsch, R. Mullen, N. Love, D. Aga, C. Bott, B. Foxman, J. Jimenez, T. Luo, K. Ramadugu, K. Wigginton. 2015. Urine diversion for nutrient recovery and micropollutant management: Results from a regional urine recycling program [Online]. Available at http://richearthinstitute.org/wp-content/uploads/2015/03/REI-WEFTEC-2015-manuscript-v1.1.pdf (verified 12 Nov. 2018). Rich Earth Institute, Brattleboro VT.

Pittman, C. 5 May 2011. Bill would reverse ban on spraying sewage on farmland. *Tampa Bay Times*.

Powlson, D.S., P.J. Gregory, W.R. Whalley, J.N. Quinton, D.W. Hopkins, A.P. Whitmore. 2011. Soil management in relation to sustainable agriculture and ecosystem services. Food Policy 36:S72-S87.

Pradhan, S., J. Holopainen, H. Heinonen-Tanski. 2009. Stored human urine supplemented with wood ash as fertilizer in tomato (*Solanum lycopersicum*) cultivation and its impacts on fruit yield and quality. J. Agric. Food Chem. 57:7612-7617.

Pradhan, S., A. Nerg, A. Sjöblom, J. Holopainen, H. Heinonen-Tanski. 2007. Use of human urine fertilizer in cultivation of cabbage (*Brassica oleracea*): Impacts on chemical, microbial, and flavor quality. J. Agric. Food Chem. 55:8657-8663.

Pradhan, S., S. Pitkänen, H. Heinonen-Tanski. 2010. Fertilizer value of urine in pumpkin (*Cucurbita maxima L.*) cultivation. Agric. Food Sci. Finl. 19:57-68.

Putnam, D.F., 1971. Composition and concentrative properties of human urine [Online]. Available at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19710023044.pdf (verified 12 Nov. 2018). National Aeronautics and Space Administration, Washington, DC.

Richard, T., N. Trautman. 1996. Cornell composting science & engineering: C/N ratio [Online]. Available at http://compost.css.cornell.edu/calc/cn_ratio.html (verified 12 Nov. 2018). Cornell Waste Management Institute, Cornell University, Ithaca, NY.

Rodhe, L., A. Stintzing, S. Steineck. 2004. Ammonia emissions after application of human urine to a clay soil for barley growth. Nutr. Cycling Agroecosyst. 68(2):191-198.

RStudio Team, 2016. RStudio: Integrated Development for R [Online]. Available at http://www.rstudio.com/ (verified 12 Nov. 2018). RStudio, Inc., Boston, MA.

Sanders, D. 2001. Collards [Online]. Available at https://content.ces.ncsu.edu/collards (verified 12 Nov. 2018). N.C. State Extension Publications, Raleigh, NC.

Shannon, M.C., C.M. Grieve. 1999. Tolerance of vegetable crops to salinity. Sci. Hort. 78:5-38.

Shresthaa, D., A. Srivastavaa, S.M. Shakyaa, J. Khadkab, B.S. Acharyac. 2013. Use of compost supplemented human urine in sweet pepper (*Capsicum annuum* L.) production. Sci. Hort. 153:8–12.

Sonon, L., U. Saha, D. Kissel. 2012. Soil salinity testing, data interpretation and recommendations. University of Georgia Extension, Circular 1019 [Online]. Available at http://extension.uga.edu/publications/detail.html?number=C1019&title=Soil%20Salinity%20Testing,%20Data%20Interpretation%20and%20Recommendations (verified 12 Nov. 2018). University of Georgia Extension, Athens, GA.

Stockholm Environment Institute, 2011. Ecological sanitation in Uganda: Inspirational success stories from the field [Online]. Available at http://www.ecosanres.org/pdf_files/EcosanStoriesInUgandaBooklet2011.pdf (verified 12 Nov. 2018). Network for Water and Sanitation Uganda, Kampala, Uganda.

Stocking, M.A. 2003. Tropical soils and food security: The next 50 years. Science 302(5649):1356-1359.

Stumpf, A.L. 2007. Waterless urinals: A technical evaluation, rev. ERDC-CERL TN-06-03 [Online]. Available at https://www.wbdg.org/FFC/ARMYCOE/COEECB/ARCHIVES/ecb_2006_7.pdf (verified 12 Nov. 2018). Engineer Research and Development Center, U.S. Army Corps of Engineers, Vicksburg, MS.

Sylvia, D.M., J.J. Fuhrmann, P.G. Hartel, D.A. Zuberer. 2005. Principles and applications of soil microbiology, 2d ed. Pearson Prentice Hall, Upper Saddle River, NJ.

Townsend-Small, A., D.E. Pataki, L.Y. Tseng, C.Y. Tsai, D. Rosso. 2011. Nitrous oxide emissions from wastewater treatment and water reclamation plants in southern California. J. Environ. Qual. 40(5):1542-50.

Troeh, F.R., J.A. Hobbs, R.L. Donahue. 2004. Soil and water conservation for productivity and environmental protection, 4th ed. Prentice Hall, Upper Saddle River, NJ.

U.S. Department of Agriculture, Agricultural Marketing Service. 2014. National Organic Program [Online]. Available at http://www.ams.usda.gov/AMSv1.0/nop (verified 12 Nov. 2018). USDA, Washington, DC.

U.S. Department of Agriculture, Agricultural Research Service. 2012. USDA plant hardiness zone map [Online]. Available at http://planthardiness.ars.usda.gov (verified 12 Nov. 2018). USDA, Washington, DC.

University of Florida, Institute of Food & Agricultural Sciences. N.D. Vegetable gardening in Florida series: Watering the vegetable garden [Online]. Available at http://gardeningsolutions.ifas.ufl.edu/plants/edibles/vegetables/watering-the-vegetable-garden.html (verified 12 Nov. 2018). University of Florida, IFAS, Gainesville, FL.

van Elsas, J.D., J.K. Jansson, J.T. Trevors (eds.). 2007. Modern soil microbiology. CRC Press, Boca Raton, FL.

Vinnerås, B., A. Nordina, C. Niwagabaa, K. Nyberg. 2008. Inactivation of bacteria and viruses in human urine depending on temperature and dilution rate. Water Research 42:4067-74.

Weinfurtner, K., S.A. Gäth, W. Kördel, C. Waida. 2009. Ecological testing of products from phosphorus recovery processes—first results. International Conference on Nutrient Recovery from Wastewater Streams. IWA Publishing, London, UK.

Wind, L. 2013. Initial chemistry and decay dynamics of deciduous leaf litter from a long-term soil-warming study in the Northeastern US [Online]. Available at http://www.mbl.edu/ses/files/2012/12/Wind-Lauren.pdf (verified 12 Nov. 2018). Allegheny College, Meadville, PA.

.

Winker, M., J. Clemens, M. Reich, H. Gulyas, R. Otterpohl. 2010. Ryegrass uptake of carbamazepine and ibuprofen applied by urine fertilization. Sci. Total Environ. 408:1902-1908.

World Health Organization. 2006. Guidelines for the safe use of wastewater, excreta and greywater, Volumes 1-4 [Online]. Available at http://www.who.int/water_sanitation_health/publications/en/ (verified 12 Nov. 2018). WHO, Geneva, Switzerland.

Zekeri, A. A. 2007. Livelihood strategies of food-insecure poor, female-headed families in rural Alabama. Psychol Rep. 101(3 Pt 2):1031-1036.

Zhu, Y-G. 2009. Soil science in the understanding of the security of food systems for health. Asia Pac. J. Clin. Nutr. 18(4):516-519.

Table 1. Composition of two batches of source-separated human urine collected and consolidated in Okaloosa County, Florida from 14 and 20 individuals, inclusively.

Date of Collection/ *No. Donors*	**Br**	**NO_3-N**	**Cl-**	**NO_2-N**	**F-**	**PO_4^{-3}**	**SO_4^{-2}**	**Total S**	**K**	**Total N (Kjeldahl)**	**Total P**	**NH_4-N**	**pH**
	mg/L												
25 Feb. 2017/ *14*	22	2.3	2500	0.42	24	430	1500	500	1400	6400	580	5700	9.2
22 Apr. 2017/ *20*	32	0.86	2100	0.42	10	420	1700	560	1300	8800	700	7700	11.6
Mean	27	1.6	2300	0.42	17	425	1600	530	1350	7600	640	6700	9.5

Table 2. Sequential ammonium and nitrate levels upon fresh source-separated human urine application to Benndale soil.

	mg/kg					
Sample No.	**12 hours NH_4-N**	**12 hours NO_3-N**	**24 hours NH_4-N**	**24 hours NO_3-N**	**2 days NH_4-N**	**2 days NO_3-N**
1	50	50	50	50	40	50
2	50	50	50	50	40	50
3	40	60	60	60	40	50
4	30	50	270	90	50	50
Mean	43	53	108	63	43	50
SD	8	4	94	16	4	0
Sample No.	**3 day NH_4-N**	**3 days NO_3-N**	**4 days NH_4-N**	**4 days NO_3-N**	**5 days NH_4-N**	**5 days NO_3-N**
1	60	60	130	130	110	140
2	50	60	130	150	120	150
3	50	50	120	150	110	160
4	50	60	140	150	120	170
Mean	53	58	130	145	115	155
SD	4	4	7	8	5	11
Sample No.	**6 days NH_4-N**	**6 days NO_3-N**	**7 days NH_4-N**	**7 days NO_3-N**	**10 days NH_4-N**	**10 days NO_3-N**
1	100	140	90	150	80	210
2	90	130	90	140	70	220
3	80	130	80	130	60	250
4	80	170	80	140	60	160
Mean	88	143	85	140	68	210
SD	8	16	5	7	8	32

Table 3. Comparison of untreated and source-separated human urine (SSHU)-treated compost for nitrate, chloride, and pH.

Sample No.	NO_3-N untreated (mg/kg)	Cl^- untreated (mg/kg)	pH untreated	NO_3-N SSHU-treated (mg/kg)	Cl^- SSHU-treated (mg/kg)	pH SSHU-treated
1	60	20	6.13	152.5	2080	6.58
2	85	7.5	6.25	232.5	2560	6.68
3	105	5	6.26	190	1915	6.76
4	110	10	6.19	302.5	2420	6.67
Mean	90	10.6	6.20	219.4	2244	6.67
SD	20	5.7	0.05	55.7	258	0.06

Table 4. Linear regression model parameter estimates of source-separated human urine (SSHU) and Miracle-Gro (M-G) effects.

X	Y	Intercept	Treatment Coefficient	Estimated Response	SE	P Value	R Value
SSHU treatment of oak leaves	NO_3-N (mg/kg)	90	129	+39	34	≤0.01	0.71
SSHU treatment of oak leaves	Cl^- (mg/kg)	11	2233	+2222	149	≤0.01	0.97
SSHU treatment of oak leaves	[H+]	6.247e-07	-4.102e-07	-2.145e-07	4.798e-08	≤0.01	0.92
mg/kg N from M-G at rate ≤ 60 mg/kg	collard biomass (g)	32	0.23	+0.23 (g)	0.045	≤0.01	0.71
mg/kg N from SSHU	residual soil Na (mg/kg)	63	-19 (from using M-G)	+19	6.6	≤0.01	0.22
mg/kg N from SSHU or M-G	NO_3-N (mg/kg)	126	0.75	+0.75	0.14	≤0.01	0.48
mg/kg N from SSHU or M-G	Cl^- (mg/kg)	4.1	0.07	+0.07	0.02	≤0.01	0.44
mg/kg N from SSHU or M-G	K (mg/kg)	15	0.42	+0.42	0.095	≤0.01	0.39
mg/kg N from SSHU or M-G	Na (mg/kg)	34	0.31	+0.31	0.040	≤0.01	0.66

Table 5. Comparison of ground raw oak leaves, untreated compost, and source-separated human urine (SSHU)-treated compost for C, N, C:N, P, K, S, Ca, Mg, Na, and pH.

Sample Type	**C** (%)	**N** (%)	**C:N**	**P** (%)	**K** (%)	**S** (%)	**Ca** (mg/kg)	**Mg** (mg/kg)	**Na** (mg/kg)	**pH**
Raw Oak Leaves	94.5	0.84	112.5	0.036	0.12	0.15	1.31	0.18	259	4.51
Untreated Oak Leaf Compost	94.0	1.01	93.7	0.047	0.19	0.16	1.77	0.25	405	6.32
SSHU-Treated Oak Leaf Compost	91.0	2.68	34.0	0.34	0.82	0.38	1.85	0.31	7684	7.28

Table 6. Mean collard green biomass and stem height in response to N treatments with source-separated human urine (SSHU) and Miracle-Gro® (M-G), and mean residual soil Cl-, K, NO3-N, P, Ca, Mg, Na, and pH.

Treatment *mg/kg total N*	**Biomass** (g)	**Stem Height** (mm)	**Cl$^-$** (mg/kg)	**K** (mg/kg)	**NO3-N** (mg/kg)	**P** (mg/kg)	**Ca** (mg/kg)	**Mg** (mg/kg)	**Na** (mg/kg)	**pH**
***SSHU** 0*	31	330	4	17	117	17	897	124	37	4.78
***SSHU** 41*	28	378	5	21	147	14	939	133	50	4.80
***SSHU** 83*	33	379	8	26	227	18	880	120	67	4.73
***SSHU** 166*	19	330	12	58	219	18	889	124	99	4.69
M-G 0	31	330	4	17	117	17	897	124	37	4.78
M-G 30	43	420	7	30	151	15	930	135	46	4.80
M-G 60	45	400	9	41	167	15	865	118	42	4.79
M-G 120	37	368	21	122	236	21	972	143	52	4.85

Figure 1. Photography of source-separated human urine (SSHU)-treated and untreated composts at the two-week point and a day after completion of a 21-day simulated rapid composting process.

SSHU-treated compost at two-week point of composting process

Untreated compost at two-week point of composting process

SSHU-treated compost a day after 21-day composting process

Untreated compost a day after 21-day composting process

Figure 2. Photography of SSHU-treated and untreated composts fifteen months after completion of a 21-day simulated rapid composting process.

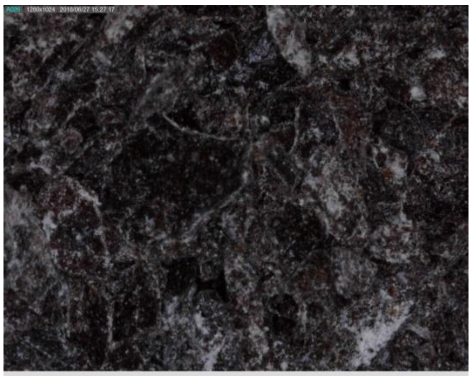
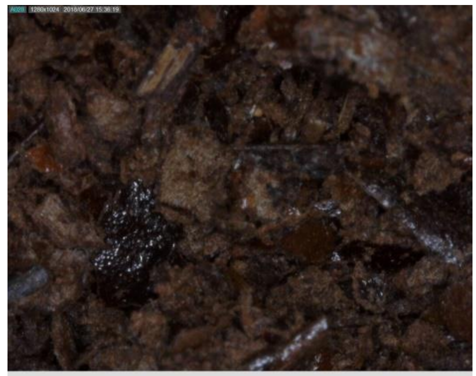
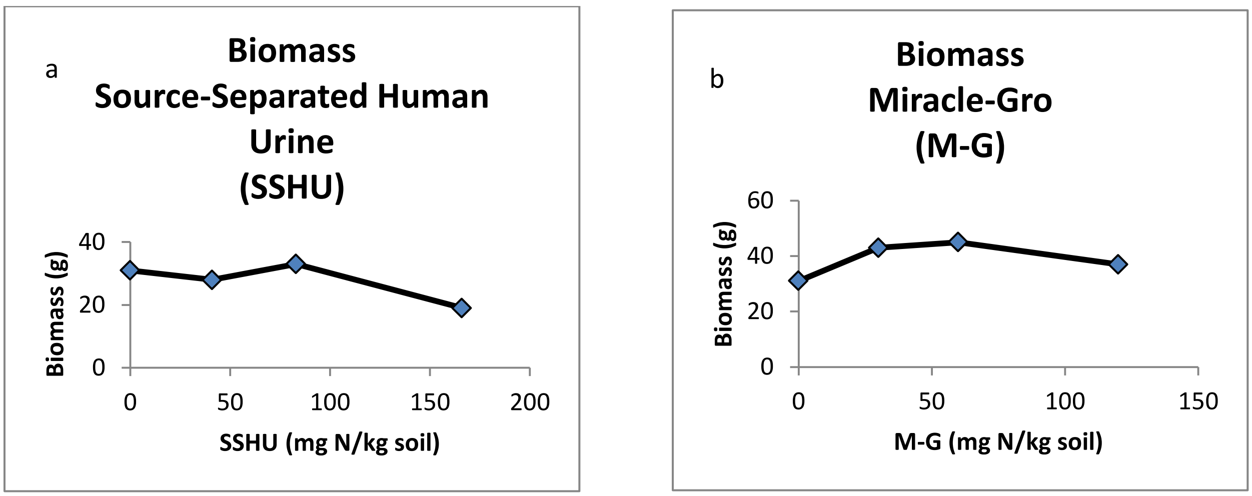
SSHU-treated compost almost fifteen months after composting process	Untreated compost almost fifteen months after composting process
	

Figure 3. Biomass by treatment.



Appendix I

Chemical analysis of soil samples extracted by Mehlich I

	mg/kg				
Sample No.	**Al**	**As**	**B**	**Ba**	**Cd**
1	634	<0.1	*0.3*	11	<0.1
2	193	<0.1	*0.3*	16	<0.1
3	573	<0.1	*0.3*	6	<0.1
Mean	467	<0.1	*0.3*	11	<0.1
SD	195	0	*0*	4	0
	Cr	***Cu***	***Fe***	***Mn***	***Mo***
1	<0.1	*2*	*17*	*109.6*	*<0.1*
2	<0.1	*1*	*18*	*113.7*	*<0.1*
3	<0.1	*1*	*19*	*133.6*	*<0.1*
Mean	<0.1	*1*	18	*119.0*	*<0.1*
SD	0	*0*	*1*	*10*	0
	Na	**Ni**	**Pb**	***Zn***	
1	43.4	*<0.1*	<0.1	*6*	
2	43.2	*<0.1*	<0.1	*6*	
3	40.5	*<0.1*	<0.1	*5*	
Mean	42.4	*<0.1*	<0.1	*5.7*	
SD	1.3	*0*	0	*0.5*	