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Experimental Design of a Long-term Study on Landscape Irrigation Using Household Graywater

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Abstract

As communities throughout the United States are becoming interested in innovated approaches to water resource sustainability, household graywater reuse for irrigation is gaining in popularity. Some states, including California, Arizona, and New Mexico, and several other counties have legalized the practice. However there are some concerns with household graywater irrigation that need further scientific study. One concern is the possibility of household graywater irrigation adversely impacting the soil environment and/or irrigated horticultural plants over the long term. Another concern is the possibility of irrigated graywater being a pathway for the spread of human diseases.

This study developed recommendations for scientific experiments to alleviate information gaps regarding household graywater irrigation impacts. Developed experimental protocols will be implemented in a future Water Environment Research Foundation (WERF) study (Phase II). This study protocols addresses:

1) Household graywater: water quality, collection, treatment, and storage;
2) Soil chemistry changes due to graywater application;
3) Graywater effects on soil microbiology;
4) Indicator organisms presence for human health considerations; and
5) Impacts on various classes of residential landscape plants.

This paper presents study findings including the recommendations made for greenhouse and prototype experiments.

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1.0 Background

Graywater[1] reuse is becoming popular in Europe, Australia, and in the Southwestern United States. Several states have legalized the practice including Arizona, California, Idaho, Nevada, New Mexico, South Dakota, Texas, Utah, and Washington. With populations increasing along Colorado's Front Range and other water short areas in the arid southwest, graywater reuse can offer an attractive alternative to development of additional water supply sources. Graywater reuse shows potential for significantly reducing residential water demand, by reducing toilet flushing and summer irrigation water use, leaving more water for additional development or instream water users (dependent on water rights).

As the practice of graywater reuse grows, the limitations of the current knowledge is becoming more apparent. Several research gaps and concerns about graywater reuse remain despite over 25 years of research. This paper will briefly cover the literature knowledge to date, identify some of the concerns and future research goals for graywater reuse, and then look at two research projects currently underway to alleviate knowledge gaps.

2.0 Literature Review

A search of the refereed literature, graywater literature, and the internet revealed that little scientific research has been done on graywater in the environment. Most available knowledge is anecdotal or inferred from other water sources such as wastewater treated effluent.

2.1 Graywater Generation Rates

Literature values for graywater generation range widely, however, most of these values are based on a small dataset from a single site. A more accurate estimate may be available from total water consumption data. Based on an AwwaRF study of 12 North American Cities in 1999, authored by Mayer, et al. 1999, the graywater generation rate can be estimated to be 25-36 gallons/day/capita, which is about 40-50% of the average indoor household water use of 63.19 gallons/day/capita.

2.2 Graywater Water Conservation Potential

Inside water use typically accounts for about half the total residential water use, and slightly more than 50 percent of inside water use is graywater. If graywater could be reused for residential irrigation and toilet flushing, summer residential water use would be reduced by an estimated 25 percent and winter water use would be reduced by nearly 50 percent. Reduced demands on the water supply means less water treatment resulting in savings to the water utility, and less wastewater saves treatment costs to the wastewater utility, increased in-stream flow between the water intake and the wastewater treatment plant discharge, and increased dilution of wastewater effluent.

Ultimately, how much water can be saved by graywater reuse depends upon climatology. In the United States, the semi-arid west must look to graywater reuse to substitute for non-potable uses. In other areas with more rainfall, a combination of

1 Graywater is defined here as all household wastewater except that from toilets and the kitchen sink.

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captured urban runoff together with graywater recycling has potential to significantly reduce demands on drinking water supplies for non-potable uses.

2.2 Graywater Quality and Composition

The physical, chemical and microbial characteristics of graywater vary based upon the sources connected to the collection system, household composition as well as the household chemical usage of the residents (Eriksson et al. 2002). Graywater contains a mixture of chemicals used in a variety of household products resulting in a complex chemical composition. The addition of household chemicals can also change the bulk chemical characteristics of the water such as pH, suspended solids, biological oxygen demand and conductivity (see for example Eriksson et al. 2002). In a study of rivers downstream of urban areas, Kolpin et al., 2002 detected numerous chemicals from household products, as well as pharmaceuticals, suggesting a residential source and the potential that they will occur in some graywater. In addition to the typical household chemicals and products, Christova-Boal et al. (1996) stated that graywater would occasionally contain oils, paints, and solvents contributed from household activities. These intermittent chemicals inputs could have detrimental effects on graywater irrigated areas.

Graywater quality data is presented in Table 1 below for three specific studies. Rose et al. (1991) is one of the most frequently referenced research papers with regard to the bacterial differences given particular sources (shower vs. laundry) and household composition (children under 12 present). Households with young children have higher bacterial concentrations according to research performed by Rose (1991). Not only did Rose (1991) find that the presence of children increases bacterial loading but also shower water is found to be higher in total and fecal coliforms than laundry water. Work presented by Casanova et al. (2001) is taken from ongoing research at the Casa Del Agua, an operational graywater demonstration project in Tuscon AZ. Eriksson et al. (2003) presented graywater constituent data in their research to determine the presence of pharmaceutical and personal care products in graywater.

As can be seen from these literature values in Table 1 graywater quality varies greatly. All of these values are taken before any treatment has taken place therefore representing a variety of influent graywater qualities. The range in constituent values needs to be considered when designing graywater reuse systems based upon the fact that no single graywater system is the same as another.

2.3 Treatment Methods

Graywater treatment methods vary widely from extremely simple systems (for instance a pantyhose filter on a laundry outflow line) to very complex systems, which produce a water equivalent to municipal wastewater effluents used for reuse. Most reports of successes and failures of graywater systems are anecdotal with little or no scientific underpinning. There is little scientifically based guidance on how to construct a residential graywater system and how to maintain it.

Most states that regulate graywater irrigation specify a simple graywater treatment system including storage and, in some states, coarse filtration. The state graywater treatment systems generally consists of a vented graywater tank with a tight locking cover, vented running P-trap on inlet pipe, screened vents for both trap and

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tank, a warning sign stating non-potable water, a 3-way valve to divert overflow graywater to the sewer system, and a cleanout pipe connected to the sewer system.

Table 1: Graywater Characterizations from Three Studies

Reference	**Eriksson (2003)**	**Rose et al. (1991)**				**Casanova (2001)**
Source	**Composite**	**Shower**	**Laundry Wash**	**Laundry Rinse**	**Composite**	**Composite**
Concentration (mg/L)	**Range**	**Range**				
Temp. (^oC)	21.6 – 28.2					
pH	7.6 – 8.6				6.54	7.47
COD	77 – 240					
BOD	26 – 130					64.85
TSS	7 – 207					35.09
Turbidity (NTU)		28 – 96	39 – 296	14 – 29	76.3	43
NH_4-N	0.02 – 0.42	0.11 – 0.37	0.1 – 3.47	0.06 – 0.33	0.74	
NO_3-N	<0.02 – 0.26				0.98	
Total-N	3.6 – 6.4				1.7	
PO_4-P					9.3	
Tot-P	0.28 – 0.779					
Sulfate					22.9	59.59
Chloride					9	20.54
Hardness					144	
Alkalinity					158	
Ca	99 – 100					
K	5.9 – 7.4					
Mg	20.8 - 23					
Na	44.7 – 98.5					
Total bacterial pop. (CFU/100mL)	4.0×10^7 – 1.5×10^8	1.0×10^7 – 1.0×10^8	1.0×10^7 - 1.0×10^8	1.0×10^7 - 1.0×10^8	6.1×10^8	
Total coliforms (CFU/100 mL)	6.0×10^3 – 3.2×10^5	1.0×10^5	199	56	2.8×10^7	8.03×10^7
Fecal coliforms (CFU/100mL)		6.0×10^3	126	25	1.82×10^4 - 7.94×10^6	5.63×10^5
Fecal Streptococci (CFU/100mL)						2.38×10^2
E. Coli (CFU/100 mL)	<100 - 2800					

Dependent on holding time, graywater storage can either beneficial or detrimental to water quality. The effect of storage on graywater water quality was studied by Dixon et al. in 1996. They discovered that graywater water quality, in terms of TSS and COD, improved when stored for 24 hours, however storage for over 48 hours could be problematic due to decreased dissolved oxygen levels. Aeration of

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the graywater could minimize any deleterious effect of storage but they noted that graywater tanks would have to be designed for settling solids.

One treatment aspect not included in many graywater systems, both commercial and state-recommended systems, is a disinfection process. Many researchers have looked at the microbiological quality aspects of graywater and potential health effects (Rose et al. 1991, Christova-Boal et al. 1996, Casanova et al. 2001). The lack of disinfection could be a potential human health risk for irrigation since, according to a study completed for the Soap and Detergent Association by the NPD Group, the majority of graywater users (93%) did not treat their graywater and many graywater users (46%) irrigated fruits and vegetables plants with graywater.

2.4 Microbial Ecology of Graywater

The primary issue for graywater with regard to microbial ecology is the potential for human exposure to pathogenic microorganisms. The presence of enteric bacteria in graywater indicates that graywater is contaminated with fecal matter and presumably pathogens, although the degree of contamination varies with source of graywater, whether children are present in the household, and graywater storage time. Risks to humans can be minimized by using properly designed graywater distribution systems with subsurface drip-irrigation. Also, pathogen exposure risks can be reduced by stopping graywater irrigation to edible plants one week prior to harvest, as suggested by Garland et al. (2000). There are several data gaps in the literature, however, especially regarding pathogen movement and survival in soil, as well as the impacts of graywater application to indigenous soil microorganisms. Studies based on wastewater effluent, animal wastes, and sewage sludge indicate that pathogens are capable of persisting for some time in soil and can move into the groundwater under certain environmental conditions. Column and field experiments are needed to assess the risk of groundwater contamination by graywater application in comparison to other sources of contamination. For example, risks may be lower with graywater due to lower graywater irrigation rates and the smaller areas of land expected to receive graywater irrigation in comparison to agricultural soils receiving large quantities of sewage sludge or animal wastes, or streams receiving wastewater effluent. Lastly, few studies have addressed the potential for graywater to impact indigenous soil microbial communities. Organic matter and nutrients in graywater may stimulate microbial growth and degradation activities in the field, but controlled experiments are needed to assess the long-term impacts of graywater constituents, including salts and potential toxins, on soil microorganisms and their important ecosystem functions.

2.6 Soil Chemistry

The transport, fate and effects of graywater chemicals applied to the soil environment depend on a combination of the properties of the chemical and the soil environment, both of which can range widely. Considerable data exist for the behavior of chemicals found in graywater when applied to soil, but essentially none of the data were developed using graywater as the application medium.

The graywater irrigation will introduce chemicals to the soil with potentially short- and long-term effects. These potential effects depend on application rate, chemical concentrations in the water, degradation rate of the chemical, sorption,

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leaching, and plant uptake. In evaluating the potential effects of graywater on soil chemistry, it should be recognized that conditions in soils evolve through a complex interplay of physical, chemical and biological processes. The result is that what may start as a change in physical conditions may lead to a larger effect on microbial communities and ultimately chemical conditions.

The direct effects of graywater on soil chemistry potentially include changes in pH, salinity, and concentrations of chemicals introduced by the graywater. Salinity not only affects plants, but also can have detrimental effects on the physical properties of soils (Halliwell et. al., 2001), such as swelling. The effect on soil pH depends on the pHs and buffering capacities of both the graywater and soil. However, the pH of the soil may be more strongly controlled by microbial activity, with anoxic conditions leading to alkalinity generation and increased pH, and oxic conditions leading to acidity.

Graywater can affect the chemistry of soils directly by producing residues of chemicals in the soil. The extent to which an organic chemical accumulates in the soil depends on a combination of the rates of degradation, how strongly it is associated with soil particles, the infiltration rate and plant uptake. It should be noted that in the process of degradation, new chemicals might be generated (Branner et al. 1999) that has greater or lesser mobility and degradability than the parent chemical. The mobility of neutral organic chemicals depends largely on the concentration of particulate organic carbon in the soil, while for chemicals with charges, it depends on the availability of oppositely charged surfaces. In the soil environment where most surfaces carry a negative charge, anionic surfactants such as LAS tend to sorb less to the soil than cationic surfactants. Unlike organic chemicals, metals are not degradable and have a greater tendency to accumulate in soils. Metals tend to sorb strongly to particles, whether organic or inorganic.

The indirect effects of graywater on soil chemistry relate primarily to the effects on microbial activity. This influence on microbial activity is through the supply of organic carbon contained in graywater. Magesan et al. (1999) found that application of wastewater with high C:N ratios and BOD clogged soils and decreased hydraulic conductivity. Depending on soil texture, application rate of graywater may have a profound effect on soil chemistry. In fine-grained, poorly drained soils, high application rates may cause extended periods of saturation that prevents penetration of oxygen into the soil, resulting in a shift from aerobic to anaerobic conditions.

Whether chemicals reach the groundwater and are transported in the aquifer depends on water application rates, how strongly the chemicals sorb to solids, distance to the water table, and the chemical degradation rates. Numerous studies have reported the enhanced mobility of chemicals caused by application of sewage sludge and treated sewage effluent (e.g., Williams et al., 2002; Said-Pullicino et al., 2004), however it is not known what components in sewage are enhancing the mobility.

Even before graywater is applied, residential landscaping soils likely have a variety of chemicals that originate from nurseries where plants were bought, prior use of the soil (e.g., as a lawn), and consumer-applied pesticides. It is has been observed in many environments that dissolved organic carbon tends to decrease the amount of chemicals sorbed to solids and increase mobility (e.g., Williams et al., 2000; Graber et

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al., 1995; Cox et al., 2001), and it might be expected that dissolved organic matter in graywater will mobilize the chemicals already existing in the soil. Of particular interest are the surfactants. By design, surfactants are able to solubilize and keep in solution chemicals that normally have low solubility. As such, surfactants are not only used in household cleaning products, but also used in soil remediation as adjuvants to leach chemicals from contaminated soils (Krogh et al., 2003).

2.5 Impact of Graywater on Plants

Household cleaning products often are sources of sodium, chloride and other salts. When sub-irrigation is used, sodium and chloride higher than 100 and 140 mg/L, respectively, may cause toxic effects to the sensitive plants (Ayers and Westcot, 1985). Boron content in irrigation water higher than 0.5-1.0 mg/L can be toxic to some sensitive trees and ornamental shrubs. Therefore, before graywater irrigation can be recommended, the existing information on the relative salinity tolerance of turfgrasses and landscape plants needs to be examined. Understanding the responses of urban landscape plants to graywater irrigation and avoiding the use of sensitive plants are critical to the long-term success of the practice.

Many studies have indicated that some species of landscape plants are quite susceptible to salinity (such as sodium and total salts) while some other plants are relatively tolerant to salinity. From a study associated with recycled wastewater, we have found that most deciduous trees are more tolerant to salt than conifers because they lose their leaves each fall thereby preventing a great degree of build up of harmful constituents from season to season. Among conifers, spruces, pines and firs appeared to be more sensitive.

However, there is very limited information on graywater irrigation on landscape plants. Most evaluations were short term. Wu et al. (1995) studied the effects of simulated graywater (high concentrations of Cl^-, Mg^{2+}, Ca^{2+}, and K^+) on growth and ion uptake of nine plant species for 12 weeks. Five species were not affected by irrigation with simulated graywater (Azalea, Japanese boxwood, Hydrangea, Raphiolepsis, and Jasmine) as evidenced by shoot growth and tolerance ratio (which was defined as the percentage of growth in graywater irrigated plants compared to the percentage of growth for the control plants). The growth of Lace fern, on the other hand, was severely affected by graywater irrigation. Generally, there was a greater reduction of growth in species that accumulated more Cl-. Tissue Ca^{2+} levels appeared to play a role in tolerance to Cl-. Higher tissue Ca levels enabled the plants to have a greater tolerance to Cl-.

In Arizona, a 2-year study was completed in 2000 to evaluate the effect on the landscape plants being irrigated with graywater around the residential areas. A drip system, buried a few inches underground was used. The study revealed that, except for a slight increase in boron, no other salt accumulations in the plants or the surrounding soil were observed. The boron detected was still below acceptable levels (NSFC, 2002).

In California, a graywater pilot project was conducted in early 1990's, which consisted of 8 graywater test systems installed at residences in LA. Soil SAR and Na was increased. However, negative effects on plant growth and quality of landscape

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plants were not observed (City of Los Angeles, 1992). The authors pointed out that any harmful effects might take a number of years to manifest.

3.0 Research Needs

Based on the literature review, the following table (Table 2) has been developed to summarize graywater research topics.

Table 2: Graywater Research Areas, Standpoints, and Goals

Graywater issue or concern	Homeowner Standpoint	Municipality/Regulatory Agency Standpoint	Research Goal
Type of treatment to install or require	Easy to maintain and cost effective treatment method.	Want effective treatment that could be recommended to customers.	Scientifically tested treatment method fulfilling homeowners and municipalities goals.
Graywater as a disease pathway	Protect household members from possible sickness due to graywater reuse.	Want graywater reuse to be safe practice from a health standpoint. Note: Many states have management practices to limit contact.	Practical health safeguards to minimize disease pathways (Effective disinfection and application methods).
Impact of graywater on soils, plants, and groundwater.	Assure that the graywater will not adversely impact their plants and soils.	Want to be able to assured that the graywater will not adversely impact soil, plants, water bodies, etc. (possible liability).	Study effect of graywater on different plants, soils, and resulting leachate.
Potential water saving	How much potable water will graywater save?	What is the water saving from implementing/ encouraging graywater reuse? What can be done with the water saved (instream uses / less raw water procurement)?	Research in different climatic areas to look at impact of graywater reuse on total water demand.

CSU is currently working on parallel research projects concerning graywater reuse which strive to alleviate some of the identified research areas. The first research project is a residential household treatment system; the second is a research project for the Water Environment Research Foundation (WERF) titled “Long-term Study on Landscape Irrigation Using Household Graywater.” These two projects are briefly described below.

4.0 Residential Household Treatment System - Work to Date at CSU

At Colorado State University, for the past two years, a household graywater experiment has been underway to examine household graywater systems. The experiment scope included retrofitting an existing residence with dual plumbing and installing a graywater system with various treatment methods. The research team has been studying the system with respect to quantity and quality of graywater generated, and effects of simple treatment e.g. aeration, filtration, and UV disinfection.

Figure 1 shows some of the research results with respect to the coliform content of graywater after being subjected to various forms of treatment. The

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experimental results indicate that a simple treatment process can significantly reduce the microbiological content of the graywater.

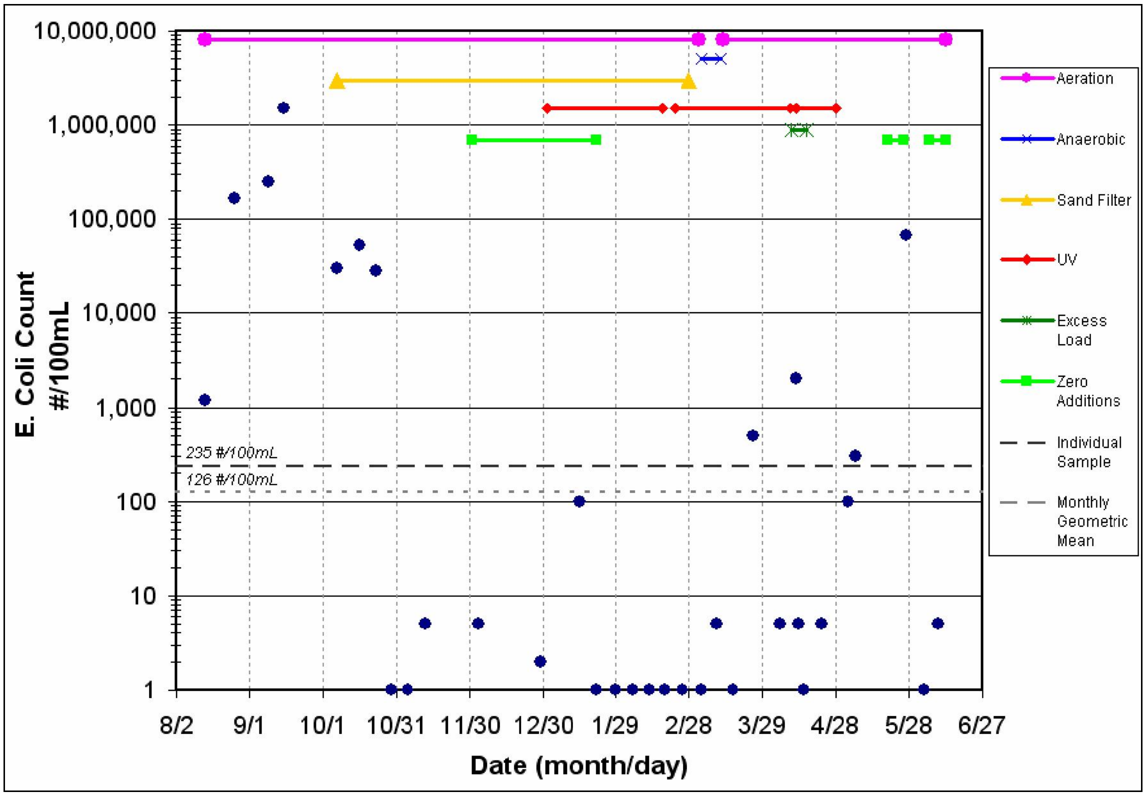

Figure 1: Residential Graywater Tank Microbiology Results (E. Coli) vs. Treatment

Note: Horizontal lines show treatment experiment being conducted at any given time.

The research team has learned a lot about residential graywater treatment systems and believes that it is possible to design systems that are both economical and maintainable by the average homeowner. Work is continuing to find an optimum treatment method.

5.0 WERF Study – Long Term Study of Household Graywater Irrigation

Several of the identified graywater research areas are being addressed in the Water Environment Research Foundation (WERF) study titled, "Long-term Study on Landscape Irrigation Using Household Graywater". The WERF study consists of developing recommendations for scientific experiments to alleviate information gaps household graywater irrigation impacts. Developed experimental protocols will be implemented in a future Water Environment Research Foundation (WERF) study (Phase II).

5.1 WERF Study – Goals

The WERF "Long-term Study on Landscape Irrigation Using Household Graywater" goals address:

1) Household graywater: water quality, collection, treatment, and storage;
2) Soil chemistry changes due to graywater application;
3) Graywater effects on soil microbiology;

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4) Indicator organisms presence for human health considerations; and
5) Impacts on various classes of residential landscape plants.

5.2 WERF Study – Experimental Protocols

The Study Team is developing a three part experimental protocol for the WERF study. The first part is greenhouse experiments under controlled conditions where accurate measurements can be made so that long-term impacts (5–15 year) results can be estimated from short-term (1-3 year) experiments. The second part is identification and examination of households with existing graywater systems. This portion of the project will survey homeowners with existing graywater systems about their operating procedures and soils, plants, irrigation water from the household will be sampled on a semi-annual basis for 1-3 years. The third part addresses prototype households with new graywater systems to investigate the impact of graywater irrigation on an existing residential landscape, not previously subjected to graywater. The prototype household experiment will be about 3 years in duration to allow the impacts of graywater irrigation to be recognized. In both the existing and prototype household graywater experiments, corresponding potable water households (similar in terms of household composition, landscaping, soil type, etc) will be tested for comparison.

At the end of the experimental period, the data gathered from the experiment classes will be compared and analyzed to determine similarities and reconcile differences between the experiment classes. The goal of the data analysis will be to develop guidelines for helping WERF subscriber utilities to make risk based decisions regarding implementation of household graywater reuse for landscape irrigation within their jurisdictional areas.

6.0 Conclusion

The research to date at Colorado State University is working to improve the scientific underpinning of graywater knowledge, much which is anecdotal. The research is bringing together information on several subjects; including graywater treatment, soil, plant and microbial impacts, to alleviate graywater reuse knowledge gaps.

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