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Article

Detergent pollutants decrease nutrient availability in soil

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SUMMARY

Household detergents contain potentially harmful surfactants that can alter microbial activity and interfere with biogeochemical cycles. Surfactants have previously been found to inhibit enzyme activity and plant growth and alter the physical properties of soil. Because detergent pollution poses a threat to ecosystems but has not been extensively studied, this study investigated the short-term effects of detergent pollution on pH and nutrient availability in soil by utilizing silty clay loam soil. Here we observed pH, phosphorus, nitrogen, and potassium levels in soil polluted with either a plant-based green detergent or a less eco-friendly detergent. Nitrogen and potassium availability levels decreased in the polluted groups. These findings support the idea that although green detergents are considered an environmentally safer choice, even these eco-friendly products have an effect on nutrient availability when introduced into soil. Overall, this study indicates that proper disposal of household products is crucial, as pollutants released into the environment can have an impact on nutrient cycling in ecosystems even in a short time period.

INTRODUCTION

Household products are a major source of harmful organic pollutants (1). Through waste disposal and residential effluent, household products such as detergents and other cleaning products are dispersed throughout the environment, posing a threat to ecosystems (1). Persistent organic pollutants pose the largest risk to soil, where pollutants form stable bonds with the organic matter, allowing them to harm crops, water quality, and human health (2). Soil pollution has been described as a "hidden danger" because it often cannot be directly assessed or visually perceived, causing growing concern worldwide (2). Understanding pollutants, and their sources, is important for pollution prevention, which greatly reduces both financial and economic costs (3).

This study focused on the environmental effects of traditional and green detergents on soil. The Environmental Protection Agency lists 'switching to "green" cleaners' as a method of pollution prevention for homes and schools, and detergent products contribute to about 10% of organic matter in domestic wastewater (4, 5). Any toxic soil pollutant, including the ingredients of detergent, can directly harm soil microorganisms (2). Historically, phosphate detergents have been known to cause eutrophication; however, regulations banning phosphate in detergents have caused companies to turn to surfactant detergents, which still have potential toxic effects connected with their surface-active properties (4). Additionally, surfactants (particularly alcohol ethoxylate, a component of the regular detergent used in this study) have an inhibitory effect on soil enzyme activity and nutrient cycling, according to previous studies (5). While moving away from phosphate detergents has helped decrease eutrophication in the environment, the surfactants replacing the phosphates still have negative environmental impacts.

The effects of detergent pollution on soil has been previously investigated in a 2018 study on laundry wastewater's effects on soil properties including saturated hydraulic conductivity, electrical conductivity, pH, exchangeable sodium percentage, cation exchange capacity, and sodium adsorption on ratio and a 2020 study on the effect of synthetic detergent on soil erosion resistance (6, 7). The first study found that the wastewater's organic micropollutants increased the pH, conductivity, and cation exchange capacity, and sodium adsorption (6). Similarly, the micropollutants reduced saturated hydraulic conductivity and cation concentrations in silty clay soil, ultimately highlighting the negative effects of detergent pollutants on soil quality (6). The more recent study tested the effects of different kinds of detergents on soil water retention curve and hydraulic conductivity to determine soil erodibility, and the researchers found that synthetic detergents significantly decrease erosion resistance in gray forest soils (7). For this study, we chose to work with silty clay loam soil, as it was the same as or similar to the soil types tested in many previous studies we found that involved surfactant pollution.

Risk assessment of pollutants remains difficult as their specific environmental impacts on ecosystems are not fully understood (2). To address this knowledge gap, this study investigates the question: how do pH, nitrogen, phosphorus, and potassium levels in soil change after organic pollutants (detergents) are introduced? In a sample of silty clay loam soil, we studied the effects on soil nutrient availability of both a detergent labeled as "green" and "plant-based," and another detergent containing typical surfactants. We studied a short time period to understand how quickly the environmental effects of detergents begin to reveal themselves. This study involved both an eco-friendly and a conventional detergent to be representative of different types of detergents and to test the environmental risks of using surfactants.

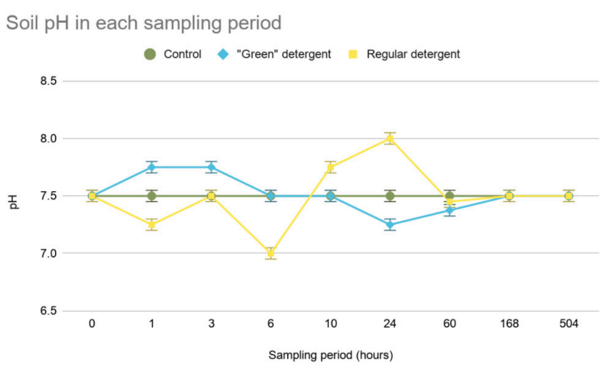
In this study, we measured changes in soil pH and the availability of nitrogen, phosphorus, and potassium (NPK) since sufficient levels are required to create optimal conditions for plant growth (8). Both high and low pH levels can lead to deficiencies of many nutrients and deterioration of soil health (8). Plants require nitrogen in amino acids, proteins, chlorophyll, and enzyme reactions, emphasizing the key role nitrogen plays in plant health and quality (9). Phosphorus, a component of DNA and RNA, is critical in plant development and seed production (9). Plants require potassium for the activation of many enzymes, efficient water use, and better resistance to extreme conditions (9). Because soil conditions and NPK levels can significantly affect plant health, this research could be helpful in determining the effects of soil pollution on living organisms. We hypothesized that both detergents would increase pH and decrease the availability of all essential nutrients, but the non-green detergent would cause more extreme and long-lasting effects. We tested nutrient availability using the LaMotte soil nutrient test kit for pH and phosphorus, nitrogen, and potassium availability. If this field is studied further in the future, we recommend that our results are verified using more advanced nutrient tests.

RESULTS

A soil sample was collected and divided into three containers as separate experimental groups; one remained uncontaminated, one was contaminated with a detergent labeled as a "green" detergent, and one was contaminated with a "regular" detergent to simulate pollution sites. Soil nutrient tests were used to measure pH, phosphorus, nitrogen, and potassium levels in each group over the study period. The pH of each contaminated group fluctuated within the first 60 hours before returning to its original level, while the pH of the control group remained constant at pH 7.5 for the entire study period (**Figure 1**). The initial soil pH was 7.5 for all groups. The pH of the soil polluted with green detergent increased to 7.75 and decreased to 7.25 within the first day, and then returned to its original pH after 168 hours. The pH of the soil polluted with the regular detergent decreased as low as 7, increased up to 8, then returned to the original pH of 7.5 after 168 hours.

Overall, nitrogen concentrations in the contaminated soils decreased over the course of the study period (**Figure 2**). Each soil sample initially contained 15 lbs/acre available nitrogen. Nitrogen availability in the control group decreased to as low as 10 lbs/acre in the first six hours but remained close to the original level for most of the experiment and increased up to 22.5 lbs/acre by the end of the study period. In the soil contaminated with the green detergent, nitrogen availability dropped between 1 and 3 hours, reaching 0 lbs/acre after 3 hours and staying under 5 lbs/acre for the remainder of the study period. Both sampling periods after 60 hours measured the nitrogen availability of this group to be 0. In the soil contaminated with regular detergent, nitrogen availability fluctuated between 15 lbs/acre and 10 lbs/acre in the first 24 hours before beginning to decrease; the lowest concentration of nitrogen measured was 2.5 lbs/acre 168 hours after contamination.

In all soil samples, the phosphorus availability was initially measured to be 200 lbs/acre. Over the study period, the availability fluctuated between 215 and 190 lbs/acre, with an



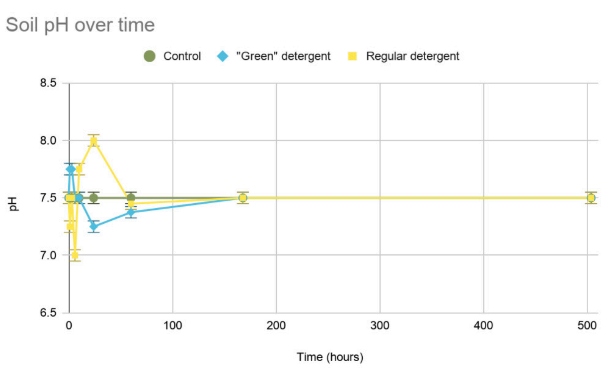
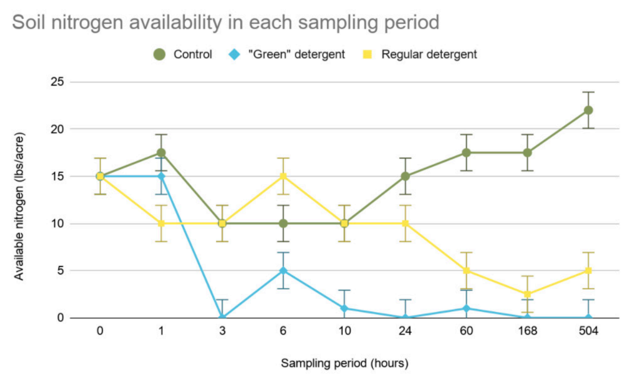


Figure 1: Soil pH over time. The upper graph shows the soil pH of each group measured in each sampling period. The lower graph shows the trend in soil pH over true time. Each line color represents one experimental group, and error bars represent the estimated standard deviations.



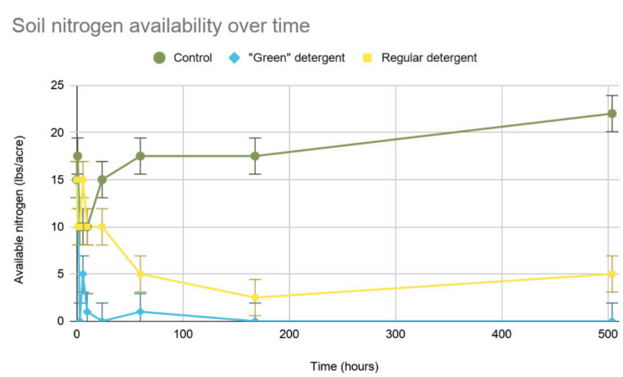


Figure 2: Nitrogen availability over time. The upper graph shows the nitrogen availability (lbs/acre) in each group measured in each sampling period. The lower graph shows the trend in soil nitrogen availability over true time. Each line color represents one experimental group, and error bars represent the estimated standard deviations.

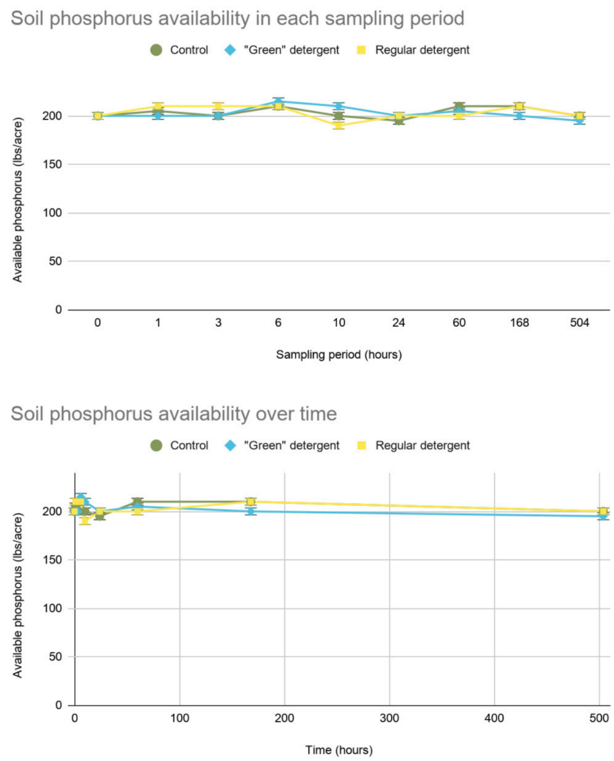


Figure 3: Phosphorus availability over time. The upper graph shows the phosphorus availability (lbs/acre) in each group measured in each sampling period. The lower graph shows the trend in soil phosphorus availability over true time. Each line color represents one experimental group, and error bars represent the estimated standard deviations.

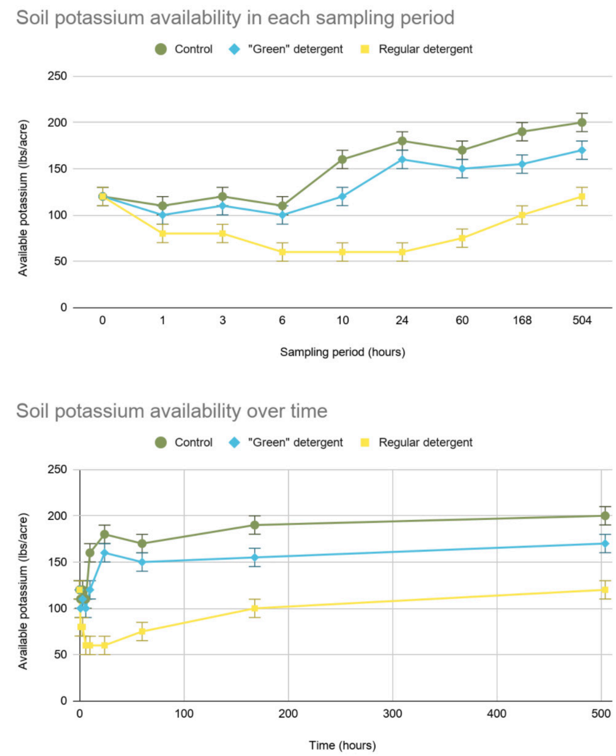


Figure 4: Potassium availability over time. The upper graph shows the potassium availability (lbs/acre) in each group measured in each sampling period. The lower graph shows the trend in soil potassium availability over true time. Each line color represents one experimental group, and error bars represent the estimated standard deviations.

average value of about 203 lbs/acre (**Figure 3**). Phosphorus availability in the control group increased as high as 210 lbs/acre and decreased as low as 195 lbs/acre. In the soil contaminated with the green detergent, phosphorus levels reached as high as 215 lbs/acre, and in the soil contaminated with regular detergent, phosphorus levels varied between 190lb/acre and 210 lbs/acre. The control group and the regular detergent group returned to 200 lbs/acre by the end of the study period, while the measurements of the green detergent group ended at 195 lbs/acre, less than one standard deviation from the original level.

The addition of detergent pollutants, particularly the regular detergent, lowered potassium availability (**Figure 4**). Each soil sample initially contained 120 lbs/acre available potassium. Potassium availability in the control group stayed between 110 and 120 lbs/acre in the first 6 hours and increased to 180 lbs/acre by 24 hours, and then increased to 200 lbs/acre by the end of the study period at 504 hours. Potassium availability in the group contaminated with the green detergent followed a similar trend but with lower amounts of potassium. The potassium availability fluctuated between 120 and 100 lbs/acre in the first 24 hours, rapidly increased to 160 lbs/acre in 24 hours, and gradually increased to 170 lbs/acre by 504 hours. In the soil polluted with regular detergent, potassium availability immediately decreased, reached 60 lbs/acre after 6 hours, and remained at the same level for at least 18 hours. After 24 hours, the amount of potassium in this group increased and reached 120 lbs/acre after 504 hours.

In Figures 1 to 4, the results of each nutrient test are displayed on two scatter plots with error bars showing the estimated standard deviation of the replicates in each dataset to represent the level of precision. In the graphs on top in each figure, data points are equally spaced to clearly show each individual data point, and in the bottom graphs, data points accurately portray the passage of time to show the uneven sampling periods and visualize immediate vs. long term results. The lines connecting the points help visualize trends over time.

DISCUSSION

The findings of this study showed that addition of household detergents to silty clay loam soil decreased the availability of nitrogen and potassium and caused short-term fluctuations in pH. There was no clear impact on phosphorus levels. While we expected to see an increase in pH with the addition of detergents, detergent pollution in our experiment resulted in both short-term increases and decreases in soil pH and no long-term effects, with the regular detergent causing larger fluctuations than the green detergent. Detergents are mixtures of compounds with varying pH levels along with pH buffers, so each compound in the mixture may have taken a different amount of time to interact with the soil and change its pH, explaining the observed fluctuations. Soil pH was important to observe since both high and low levels can lead to deficiencies of many nutrients and deterioration of soil health

(8). Clay soils and soils with more organic matter content are better able to resist drops and rises in pH than sandy soils, so these rapid changes in pH may have had more severe effects if this experiment was performed using less resistant soil (8). Additionally, higher concentration of detergent could have overpowered the soil's ability to buffer.

As hypothesized, the addition of detergent pollutants decreased nitrogen and potassium availability. The observed trends in both nitrogen and phosphorus availability were likely caused by two main factors: chemical interactions between the detergents and soil and the effects of the detergents on microbes involved in nutrient cycling. Because chemical reactions take place relatively quickly, we believe they had a considerable effect on the shorter-term trends. Microbial degradation of surfactants takes several days or weeks, and the effects of surfactants on enzyme activity in previous studies have been measured over several weeks to months; thus, microbial activity was likely the main cause of the longer-term (168+ hours) trends in nutrient availability (5).

The addition of surfactants in soil may cause chemical reactions that may interfere with the transport of nutrients and reduce soil quality for microorganisms (10). Specifically, both detergents from this experiment contain sodium salts, which have been found to be detrimental to soil physicochemical properties (11). Soils affected by sodium deteriorate because of changes in the proportions of certain cations and anions, which may include potassium and nitrate ions that are present in the soil solution and on the exchange sites (12). Because the nutrient tests used in this experiment measure the concentrations of nutrients in a soluble, exchangeable form, sodium may have interfered with both potassium and nitrogen availability. Due to their chemical similarities, sodium ions prevent the uptake of potassium ions (11). Additionally, in previous studies the use of surfactants has been recognized as a cause of decreased soil hydraulic conductivity (10). Surfactants are adsorbed into clays and organic materials, which may slow down the overall flow of nutrients (10).

Nitrogen availability decreased following the addition of detergents, with the green detergent causing a faster and more extreme decrease, contrary to the hypothesis that the regular detergent would cause a larger decrease. A possible explanation for the trends after 168 hours is that higher carbon content in soil from the detergents biodegrading may have caused a nitrogen deficiency, as nitrogen is used up when microorganisms decompose organic matter (13). Knowing that most surfactants have half-lives of about 3 weeks or less, we believe that this could have affected microbial activity during the two last measurements of the study period (10). The regular detergent included more inorganic compounds and fewer anaerobically biodegradable surfactants, such as alkylbenzene sulfonate, while the green detergent was more readily biodegradable, using surfactants such as sodium lauryl sulfate, which mostly degrades within 50-140 hours, explaining the faster and larger-scale decrease in nitrogen availability (14,15).

In the last few sampling periods, potassium availability showed a relative increase but still stayed lower than the levels in the control group, with the group contaminated by the conventional detergent showing the lowest levels of potassium. Surfactants in silty clay loam soil have been previously found to inhibit the activity of enzymes involved in nutrient cycling (5). Also, surfactants serve as carbon sources for certain microbes and are toxic to others, interfering with the composition and structure of microbial communities (10). Since most potassium in soil is in unavailable forms, potassium availability depends on the activity of potassium-solubilizing bacteria, which may have been affected by the addition of surfactants (16).

Although it was hypothesized that adding detergent pollutants would decrease phosphorus availability, there were no clear differences between the control group and the contaminated groups. Each group fluctuated around the same range, usually less than one standard deviation away from each other, suggesting that surfactants do not significantly increase or decrease the amount of phosphorus in soil. However, adding a higher concentration of detergent or using more precise nutrient tests may yield different results.

Possible sources of error in this study are human error in using nutrient tests and potential outside factors affecting the soil, such as additional chemical pollutants existing in the soil and the microbial community. The equal concentrations of the detergents may have made this study less applicable to real pollution, since the amount used per load of laundry for the regular detergent was about twice that of the green detergent. The sample size and scope of this experiment were relatively small due to limited resources, so further experimentation in this field would be helpful in confirming and expanding these results. Further research on surfactant pollution and nutrient availability in soil could focus on a broader range of household products and how they affect soil, the long-term effects of detergents in soil, the severity of the effects of different concentrations of surfactants in soil, the impact of detergent pollution on soil-based ecosystems, and the effects of detergents on phosphorus availability. Additionally, direct testing on microbial activity after the addition of detergent pollutants could help determine the validity of our proposal that changes in microbial activity may account for differences in soluble nutrient availability over time.

The results support the idea that even "eco-friendly" products affect nutrient availability when introduced into soil. Overall, this study concludes that proper disposal of household products is crucial, as pollutants released into the environment can have an impact on nutrient cycling in ecosystems even in a short time period. This shows the importance of pollution prevention, and adds to the findings of the two previous detergent pollution studies discussed in the introduction. Compared to the study on how laundry greywater affects soil properties from 2018 (6), the baseline pH of the soil samples we used was much higher, at a neutral pH as opposed to an original pH of 3.85 as observed in the previous study (6). The pH had an overall increase in that study, but this was not the case in our study potentially because the buffers in their detergents likely brought the pH up rather than bringing it back to the original acidic level. This suggests that the properties of soil before the addition of detergent pollutants affects the extent of the detergents' impact. Another study published in 2020 found that detergent pollution makes soils more vulnerable to degradation, likely caused by changes in the soil's chemical composition (7). The unstable soil pH and changes in NPK concentrations we found may have contributed to this result. Ultimately, our study strongly supports the previous conclusion that detergents in wastewater should be reduced to a minimum concentration and regulations for proper disposal must be adopted (6).

MATERIALS AND METHODS

In this controlled study, two containers of soil were each contaminated with a different brand of laundry detergent with a unique chemical composition (**Table 1**), and changes in nutrient availability and pH were observed over the following three weeks and compared to a third uncontaminated container of soil, used as a control group (**Figure 5**). This study was conducted under controlled conditions, in an indoor, aerobic environment. A silty clay loam soil sample (10YR 4/1 on Munsell color chart) was collected from a level, grassy area away from human fertilizer input in Menlo Park, California using a soil sampling tube and divided into three 120 g containers with lids. 0.6 g of Persil ProClean Liquid Laundry Detergent (a typical detergent) was dissolved in about 10 g of water, and 0.6 g of Seventh Generation Natural Laundry Detergent (a green detergent, labeled as plant-based and eco-friendly) was dissolved in 10g of water in a separate container, and each diluted contaminant was mixed evenly throughout one of the soil samples to simulate a pollution site, with a detergent concentration of about 5000 ppm. The recommended amount per load of laundry was 22 mL for the green detergent and 46 mL for the regular detergent, but equal concentrations were used for this experiment. As a control, an equal amount of pure water was mixed into one of the soil samples to keep soil moisture constant. The soil samples were stored together in a controlled environment with lids on to minimize outside factors influencing the results. Using a LaMotte soil nutrient test kit, pH and phosphorus, nitrogen, and potassium availability in each sample were tested 0, 1, 3, 6, 10, 24, 60, 168, and 504 hours after the initial

Table 1: Chemical composition of Persil ProClean Liquid Laundry Detergent vs. Seventh Generation Natural Laundry Detergent, as listed by manufacturers.

Persil ProClean Liquid Laundry Detergent	Seventh Generation Natural Laundry Detergent
Water	Water
Alcohol Ethoxy Sulfate	Laureth-6 (Plant-Derived Cleaning Agent)
Alcohol Ethoxylate	Sodium Lauryl Sulfate (Plant-Derived Cleaning Agent)
Alkylbenzene Sulfonate	Sodium Citrate (Plant-Derived Water Softener)
Sodium Citrate	Glycerin (Plant-Derived Enzyme Stabilizer)
Sodium Soap	Sodium Chloride (Mineral-Based Viscosity Modifier)
Ethoxylated Polyethyleneimine	Oleic Acid (Plant-Derived Anti-Foaming Agent)
Propylene Glycol	Protease Enzyme Blend (Plant-Based Oil Remover)
Protease	Sodium Hydroxide (Mineral-Based Ph Adjuster)
Tetrasodium Edta	Amylase Enzyme Blend (Plant-Based Soil Remover)
Sodium Borate	Mannanase Enzyme Blend (Plant-Based Soil Remover)
Fragrance	Calcium Chloride (Mineral-Based Enzyme Stabilizer)
Ethanol	Citric Acid (Plant-Derived Ph Adjuster)
Amylase	Octylisothiazolinone (Synthetic Preservative)
Sodium Formate	Methylisothiazolinone (Synthetic Preservative)
Cellulase	
Mannanase	
Disodium Distyryl Biphenyl Disulfonate	
Polydimethylsiloxane	
Blue Dye	
Lilial	
3-methyl-4-(2, 6, 6-trimethyl-2-cyclohexene-1-yl)-3-buten-2-one	
Amyl Cinnamal	
Benzyl Salicylate	
d-limonene	
Eugenol	
Geraniol	
Hexylcinnamaldehyde	
Linalool	

Figure 5: Experimental setup for this study. Two containers of soil were each contaminated with one of the two types of detergent, the "green" (left) or "regular" (right) detergent, while one container was left without any contaminants as a control.

contamination to study both the short-term and longer-term trends in nutrient availability. Measurements were taken by using nutrient extracting solutions on small amounts of each sample, using nutrient indicators, and comparing the tests to a color chart. During testing, a random 20% of the tests were repeated to ensure precision and estimate the amount of variation in the results by calculating the standard deviations between the two tests. The study was limited by the number of available nutrient tests, about 40 tests. The average standard deviations for pH, nitrogen, phosphorus, and potassium tests were 0.495, 1.919 lbs/acre, 4.041 lbs/acre, and 9.899 lbs/acre, respectively.

The test kit includes a pH indicator solution, which detects the presence of H^+ and OH- ions when soil is mixed in, using a universal indicator. For the NPK tests, the LaMotte kit measures the availability of nutrients in forms available for plant intake, such as soluble nitrates. For NPK, we separated compounds from the soil using an extracting tablet or powder and used a nitrogen, phosphorus, or potassium indicator solution to measure the amount we extracted. We found the concentrations in lbs/acre by comparing the colors of the indicators to a color chart provided by the kit. Although this kit is not as accurate and detailed as a complete chemical analysis of the samples, this was a practical option given the budget and limitations of this study and could still provide sufficient information to compare the changes in nutrient availability between experimental groups.

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