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Reaping the Benefits of Conservation Tillage: Implications of Increased Soil Organic Matter and Aggregation in Surface Soils

Kenna Rewcastle
kenerewc@vols.utk.edu

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PURSUIT

Reaping the benefits of conservation tillage: Implications of increased soil organic matter and aggregation in surface soils

KENNA REWCASTLE
Advisor: Dr. Jie Zhuang

In light of the US Department of Agriculture's initiatives to reduce herbicide application on agricultural lands by 10% and increase soil carbon sequestration by 15%, the agriculture industry is in need of a cultivation practice that allows for more efficient herbicide application and fosters soil carbon accumulation. Our study presents a broad evaluation of the ability of conservation tillage techniques to meet the demands of this goal while maintaining high crop yields. We investigate the implications of increased organic matter and improved soil structure in conservation tillage soils for the protection and storage of soil carbon within stable microaggregates and the retention of herbicide chemicals in the bulk soil. To do so, we complete a soil respiration study to analyze carbon storage in different soil size fractions and design a novel column system to analyze herbicide transport through surface soils. The results of this preliminary study suggest that conservation tillage is a viable method of fulfilling the USDA's initiatives to ensure the sustainability of the agriculture industry in the face of climate change.

The author can be reached at kenerewc@vols.utk.edu.

Introduction

Since the development of effective herbicides in the 1940s, farmers have begun abandoning conventional tillage methods as a weed-prevention mechanism to instead reap the soil quality improvements that conservation tillage agriculture stimulates. This transition is occurring at a time when the US Department of Agriculture has issued the Agriculture and Food Research Initiative which includes amongst its goals a challenge to reduce herbicide application by 10% and increase soil carbon sequestration by 15% in order to mitigate and adapt to climate change (USDA National Institute of Food and Agriculture 2008). These changes must occur while simultaneously maintaining high levels of productivity, and a growing body of research indicates that widespread adoption of conservation tillage farming will allow our agricultural industry to accomplish more efficient uses of herbicide chemicals and increased terrestrial carbon sequestration (Huggins and Reganold 2008, Lal 1976).

Conservation tillage practices do indeed result in several significant benefits for the farmers that employ these methods. First and foremost, use of conservation tillage reduces the erosion of valuable topsoil by an estimated 60% to 90% when compared to conventional tillage methods (Huggins and Reganold 2008). Soil organic matter (SOM) increases in the surface horizons when plowing ceases, effectively reducing the rate of biological oxidation of SOM and preventing soil erosion (Huggins and Reganold 2008, Angers et al. 1997, Reicosky et al. 1995, Karlen et al. 1994, Mielke et al. 1986, Doran 1980, Lal 1976). Other metrics of soil health, such as soil content of essential nutrients like organic and inorganic N, P, K^+, Ca^{2+}, and Mg^{2+} increase under no-till farming (Angers et al. 1997, Doran 1980, Lal 1976).

Several secondary benefits stem from the accumulation of SOM through the use of conservation tillage practices. Chemically, SOM contains a diversity of surface functional groups that allow the soil to bind and retain many agrochemicals that would otherwise be repelled by soil mineral particles (Arias-Estévez et al. 2008, Bollag et al. 1992, Senesi 1992). SOM content, especially fulvic and humic acid concentrations, are the strongest predictors of agrochemical retention, with soil structure and compaction also influencing the interaction between these organic molecules and the soil system (Arias-Estévez et al. 2008, Bollag et al. 1992). Furthermore, conservation tillage drives enhanced water infiltration and water-holding capacity in surface soils by increasing the SOM content in affected agricultural systems (Franzluebbers 2002, Hudson 1994).

In soils with increased SOM content, this organic matter contributes to increased macroaggregation of soil particles and increased stability of the soil structure (Beare et al. 1994, Oades 1984, Tisdall and Oades 1982). The formation of these conglomerate units also protects the organic matter that becomes encapsulated in soil pores as the aggregates form (Balesdent et al. 2000). Because the implementation of reduced-till practices minimizes soil disturbance, the rate of macroaggregate turnover is drastically reduced, further stabilizing the soil carbon that is bound within the aggregate structures (Six et al. 2000). These mechanisms of protecting soil carbon held in smaller soil pores within aggregates from physical and biological degradation may allow conservation tillage to be used as a method of soil carbon sequestration, where organic matter accumulates in the soil instead of turning over quickly in conventional tillage systems (Kern and Johnson 1993, Smith et al. 1998).

While SOM clearly plays a role in restructuring the soil pore network through driving aggregation and increased structural stability in the surface soil, my research aims to clarify the implications of these physical changes stemming from aggregation for soil respiration and herbicide transport through the soil medium. I hypothesize that: 1) SOM's role in aggregation will allow for greater protection of soil carbon from microbial degradation in stable microaggregate structures, and 2) SOM's chemical nature will allow soils with greater SOM content to better retain herbicides by binding these agrochemicals to the surface of SOM particles. These questions directly address the suitability of conservation tillage practices, a technique that stimulates SOM accumulation, in fulfilling the USDA's goals to establish a more sustainable and environmentally sound agriculture sector.

General Soil Characteristics

The soils used in this study were obtained from the University of Tennessee Organic Farm from a study conducted by Dr. David Butler of the Department of Plant Sciences. The treatment used to cultivate these soils in this agricultural study was a continuous organic vegetable crop rotation used with a clover cover crop under reduced-till conditions. These soils have been cultivated under this treatment for two years before collection. Soils were taken from three different replicate plots for each treatment. Table 1 summarizes relevant soil physical properties and compares the structure and organic matter content of these soils to those that had been subjected to conventional tillage practices.

Treatment	Continuous organic vegetable cultivation, clover cover crop, reduced-till	Conventional tillage, continuous vegetable cultivation
Duration of Treatment	2 years	2 years
Microaggregate Content (%)	30.95%	8% (Six et al. 2000)
Macroaggregate Content (%)	63.09%	30% (Six et al. 2000)
Bulk Soil Total Carbon (%)	1.55%	1.28%
Microagg Total Carbon (%)	1.36%	1.08%

Tab. 1: Conservation tillage (reduced-till management practices) results in improved soil structure by stimulating an increase in soil carbon content and fostering aggregate formation. The physical properties of reduced-till soils are compared to those of conventional-till soil. The aggregate content values highlighted in orange come from Six et al. (2000), a study where the treatment had been applied for 9 years for the sake of comparison.

Soil Carbon Sequestration in Conservation Tillage Soils

As the presence of SOM under minimal disturbance stimulates aggregate formation, the structure of the surface improves while simultaneously protecting the soil carbon that is encapsulated in the pore structure of micro- and macroaggregates. This process of encapsulation physically protects SOM from aeration and restricts microbial access to the organic matter bound in the smallest pores, preventing microbial degradation of these organic substrates (Balesdent et al. 2000). In this study, we analyze the role of microaggregates, the most stable soil fraction, in shielding soil carbon from microbial degradation during soil respiration.

Methods

Five 20g samples of bulk soil were placed in water- and air-tight stainless steel tubes for incubation. For the microaggregate samples, water-stable microaggregates were extracted from (53 – 250 μm) from the bulk soil samples by sieving allowing the soils to absorb deionized water to field capacity over night, and then gently shaking the soil sample through wire mesh screens while immersed in deionized water. The extracted microaggregates were then freeze-dried using lyophilizer. 10 g of extracted microaggregates were combined with 10 g of macroaggregate-sized pure quartz sand particles to maintain the soil particle size-distribution of the natural soil within the incubation vessel. Soil moisture content was maintained at 20% of sample mass (the mass of the soil sample plus the mass of soil water). The incubation tubes were placed in a 25 °C incubation bath, and a constant flow rate of 80 mL/min was maintained. All air entering the incubation tubes was first passed through a desiccator that removed any ambient CO_2 from the gas flow. The CO_2

efflux released during microbial soil respiration was measured using a LiCOR infrared gas analyzer. Soil respiration measurements were recorded every hour until the rate of CO_2 discharge peaked, after which measurements were taken daily for a total duration of 21 days. Release of CO2 from the soil incubators during respiration at each time step was compared between microaggregate samples and bulk soil samples using a Mann Whitney U test. This test allowed us to evaluate the differences between respiration of organic matter stored in soil microaggregates as opposed to respiration occurring in the bulk soil as a whole.

Results

Soil microaggregates are the dominant soil size fraction involved in protection and storage of organic matter in the soil system ($p = 0.001$) (Figure 1). These results support the idea of a hierarchical soil structure, where organic matter is encapsulated in increasingly smaller aggregate particles that adhere to one another in the formation of larger macroaggregates. SOM held in the smallest micropores within the microaggregate structures is, to some degree, inaccessible to the soil microbes involved in degrading this soil carbon during soil respiration. Therefore, because conservation tillage practices stimulate the formation of the microaggregates that are involved in storing and protecting carbon in the depths of the micropore network, conservation tillage can be used as a mechanism of soil carbon sequestration in accordance with USDA climate mitigation and adaptation goals.

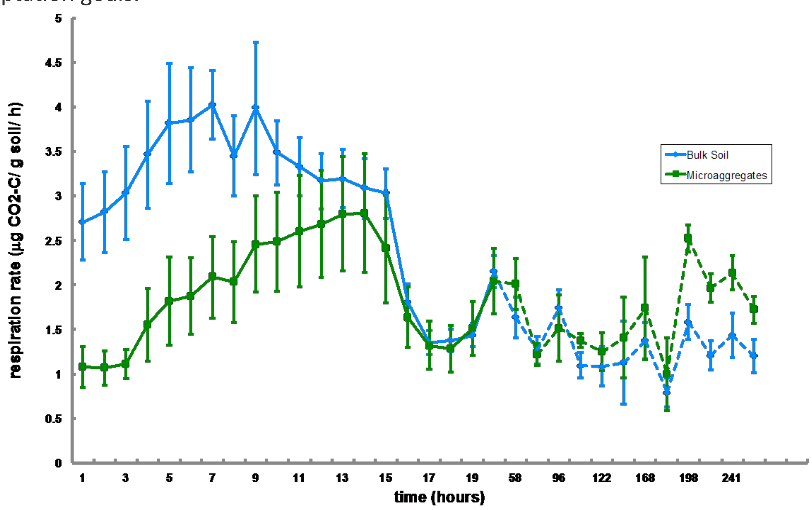

Fig. 1: Soil microaggregates are more effective than the bulk soil size-fraction in storing and protecting SOM against microbial degradation during soil respiration ($p = 0.001$). Error bars represent the standard deviation of the respiration rate from the average respiration rate amongst all replicates at each time step Dotted lines indicate the transition to daily instead of hourly measurements of soil respiration after respiration levels had peaked.

The Role of Soil Organic Matter in Retaining Herbicide Chemicals

To achieve the USDA's AFRI goal of reducing herbicide application by 10% while maintaining current levels of agricultural productivity, a more effective method of herbicide use must be employed. As already described in detail, conservation tillage results in an accumulation of SOM that has a diverse array of functional groups necessary for binding and retaining herbicides in the soil system (Arias-Estévez et al. 2008, Bollag et al. 1992, Senesi 1992).

Herbicide retention in agricultural soils would increase the longevity of herbicide, meaning that a single herbicide application would be active in the soil for a longer period of time as opposed to readily leaching out of the system or quickly degrading due to rapid exposure to microbial activity. This study analyzes the role of SOM and soil aggregate structure in retaining herbicides in soils that have been managed using conservation tillage practices.

Methods

With the help of the University of Tennessee Biological Facility Services, we designed and fabricated a stainless steel column system coupled with a high-pressure liquid chromatography (HPLC) pump and a fraction collector (Figure 2). The materials used in the column system were chosen to avoid any interactions between the herbicide chemical and plastic components of the column system. We selected the herbicide Alachlor for this study because of its widespread use in the agriculture industry and because Alachlor is one of the few commercially available deuteratic herbicides, a property that we plan to take advantage of in future small angle neutron scattering (SANS) studies that will analyze the diffusion of herbicide molecules into the soil pore network. The experimental solution contains a 5 ppm concentration of Alachlor which reflects the manufacturer's recommended application concentration for agricultural use.

To investigate the importance of soil structure on herbicide retention, we again extracted microaggregates from the bulk soil to compare herbicide retention in these highly stable aggregates as compared to herbicide retention in the bulk soil as a whole. Then, to explicitly study the role of soil organic matter in retaining herbicides, we compared herbicide retention in bulk and microaggregate soils when the organic matter was left intact and when the organic matter was removed using combustion. These two variables, SOM presence and soil size-fraction, were crossed in a factorial design and all four resulting treatments were replicated twice, totaling to eight individual column trials. Approximately 10 g of soil (bulk soil or isolated microaggregates) were packed into each column, and the exact mass of soil was recorded so that herbicide retention could be standardized by the amount of soil present in the column.

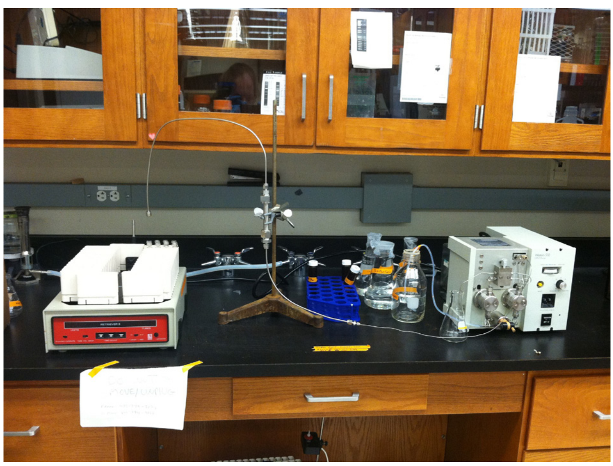

Fig. 2: This picture depicts the custom-designed soil column system used in this study. Depicted to the far right is the HPLC pump which actively pumped fluid through the Teflon and stainless steel tubing to the soil column. Fluid flowing out of the soil column was collected at regular intervals in quartz vials by a fraction collector system.

Four distinct fluids were passed through the soil column in this study. In the first phase, a 5 ppm NaCl background solution was introduced to the soil column in order to fill all pore space with an initial fluid. In the second phase, a 5 ppm Alachlor solution dissolved in 5 ppm NaCl was pumped into the column for 23 pore volumes. A pore volume (PV) here is defined as the sum volume of all pore space present in the soil system and was calculated using the known volume of the soil column, the mass of soil contained in the column, and the bulk density and porosity inherent to the soil. After the experimental solution had been introduced, the column was again flushed with an NaCl solution to dislodge any loosely bound herbicide from the soil system. Finally, an ethanol solution was used to mobilize the Alachlor, a bulky, aromatic compound that dissolves well in organic alcohols. This final flush allowed us to analyze how tightly the herbicide remaining in the soil column was bound to the soil organic matter and mineral surfaces. All fluids were pumped through the soil column at a rate of 0.22 mL/min, a rate that is reflective of the natural hydrological movement that agricultural soils experience.

Once the column effluent was collected in quartz vials, the Alachlor was extracted from the saline background solution using an ethyl acetate solvent so that the concentration of Alachlor in the effluent could be measured using gas chromatography-mass spectrometry

(GCMS). The concentration of Alachlor in the effluent was plotted against the effective PV to construct an herbicide transport diagram. This procedure was carried out for the bulk soil and microaggregate samples with SOM intact and combusted.

Logistic curves were fitted to each herbicide transport curve, and the parameters that characterize the shape of these curves were compared using a T-test to analyze the influence of SOM presence and soil structural stability (microaggregate soil fraction vs. bulk soil) on herbicide retention (Equation 1). In this equation, C is the concentration of herbicide at pore volume (PV) t, K is the 'carrying capacity' of the model, or the concentration of herbicide on which the effluent stabilizes over time. We analyzed several parameters that influence the shape of the logistic curves that describe herbicide transport in soils with and without SOM present, and between bulk soil and microaggregate size fractions. Here, 'asym' is the asymptote around which the model stabilizes (Equation 2), 'xmid' is the PV at which the inflection point in the logistic curve occurs (Equation 3), and 'scale' is the scaling parameter for the x-axis (Equation 4). The parameter r, in each of these definitions, is the growth rate for the model. C_0 represents the initial herbicide concentration at the start of each herbicide transport column experiment

$$C = \frac{K}{1+e^{C_0+rt}} \qquad (1)$$

$$asym = K \qquad (2)$$

$$xmid = \frac{-C_0}{r} \qquad (3)$$

$$scal = \frac{-1}{r} \qquad (4)$$

Additionally, the percentages of Alachlor retained by each soil sample were calculated and compared using a T-test, and the time of soil herbicide saturation for each soil was also compared using a T-test.

Results

Our results suggest that soil organic matter plays a vital role in retaining herbicide chemicals in the soil system (Figure 3). Logistic curves were fit to each individual herbicide transport curves with a fit ranging from $0.753 < R^2 < 0.973$. However, due to the low replication inherent in this preliminary study, our results lack statistical significance, and our conclusions, as such, are based on the trends observed in the few replicates present. In both the microaggregate and bulk soil size fractions, removing the SOM seemed to impair the soil's ability to retain herbicides, and trends showed that more herbicide was retained when SOM was present ($p = 0.413$). SOM presence did not significantly change the parameters that describe herbicide transport through the soil (asym $p = 0.485$, xmid $p = 0.114$, scale $p = 0.457$). Soil structural stability (microaggregates vs. bulk soil) also did not affect the shape of the herbicide transport curves (asym $p = 0.563$, xmid $p = 0.651$, scale $p = 0.657$).

Observationally, the data suggest that microaggregates retained less herbicide than was retained by the bulk soil, indicating that aggregate stability may not be an important factor in herbicide retention. This conclusion was not supported statistically owing to the small sample size used in this study ($p = 0.521$) (Figure 4). However, this effect may also stem from a flaw in the experimental design, where air bubbles that fill the smallest micropores within soil microaggregates may become trapped in the column so that the herbicide solution completely bypasses the internal pores within soil microaggregates. In future studies, this problem could be avoided by first flushing the column with CO2 gas that will readily dissolve into the herbicide solution, eliminating this 'pore-bypassing' effect.

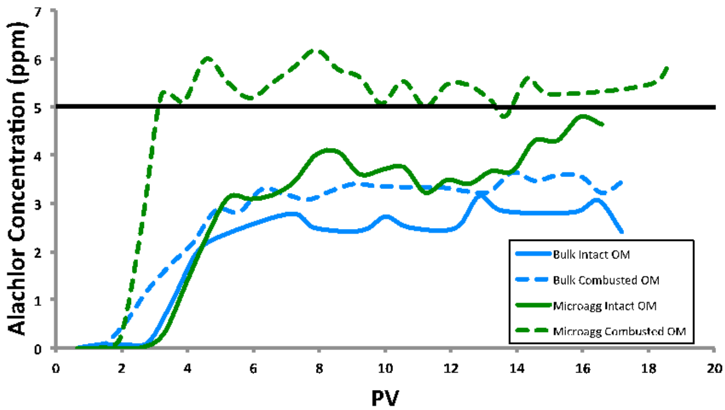

Fig. 3: In these herbicide transport curves, it seems that removing OM from the soil impedes the soils' ability to retain herbicide, and more herbicide is therefore released into the column effluent (asym $p = 0.485$, xmid $p = 0.114$, scale $p = 0.457$). Bulk soil seems to retain more herbicide than does the isolated microaggregate size fraction (asym $p = 0.563$, xmid $p = 0.651$, scale $p = 0.657$).

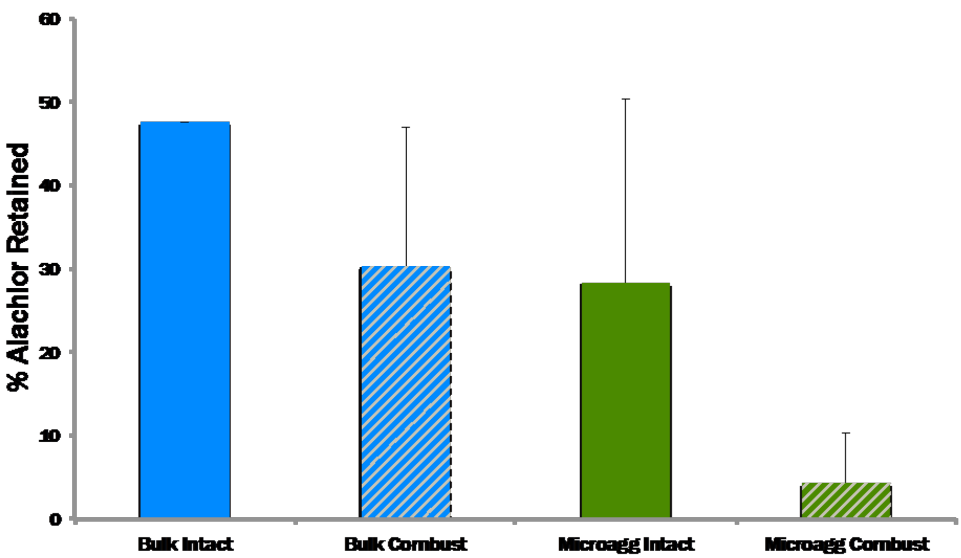

Fig. 4: Less herbicide may be retained by soils when SOM is removed via combustion ($p = 0.413$). Bulk soils with SOM intact seem to be best at retaining herbicides that are pumped through the soil column, and microaggregate soils with SOM removed seem to retain the least amount of herbicides overall ($p = 0.521$).

Finally, it is also apparent that the presence of SOM allows soils to retain herbicides for much longer than soils without SOM (p = 0.001). In other words, SOM retards the release of herbicide from the soil system and delays the point of herbicide saturation (Figure 5).

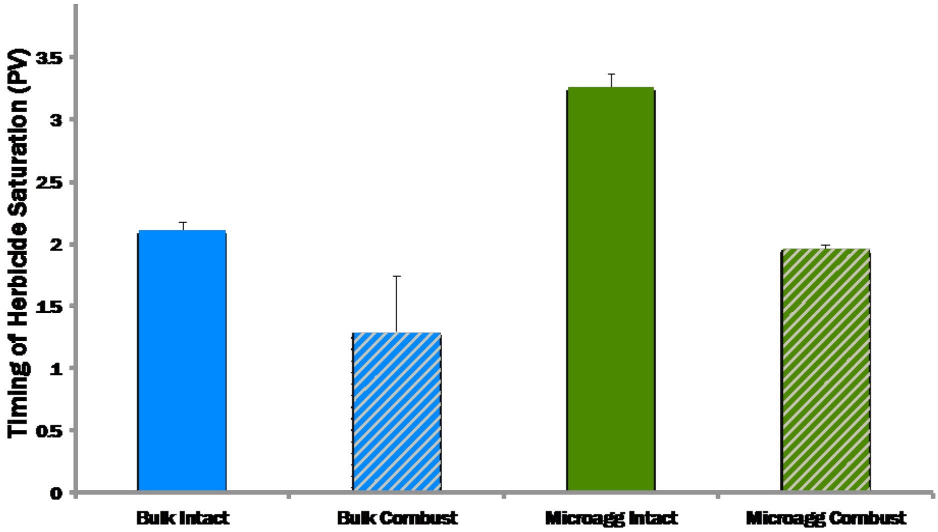

Fig. 5: SOM slows the release of herbicide into the soil solution and delays the point of herbicide saturation (p = 0. 001). Microaggregate soils in which SOM is present are able to retain herbicide for the longest before becoming saturated and slowly releasing additional herbicide into the soil solution.

Increasing herbicide retention in soils is one way to increase the efficacy of herbicide application because it lengthens the time period over which a single application of herbicide will remain active in deterring weed growth. Because conservation tillage, by causing a buildup of SOM, will foster herbicide retention in the surface soils of agricultural fields, conservation tillage again becomes a way for farmer's to balance the USDA's environmental sustainability initiatives that encourage the reduction of herbicide usage while maintaining competitive crop yields.

Conclusions

In the USDA Agriculture and Food Research Initiative, the federal government has challenged farmers to strike a balance between environmentally sustainable agriculture under the constraints of climate change while simultaneously maintaining or even increasing agricultural productivity to feed the growing global population. Achieving these goals will require the widespread adoption of agricultural techniques that involve more efficient use of herbicides and foster long-term carbon storage in the soil. By reducing disturbance of the surface soil, conservation tillage practices results in an accumulation of SOM that also stimulates aggregation and improved soil structure. Although limited replication diminished the statistical significance of our study, our results observationally suggest that this increase in organic matter and heightened aggregation has consequences for enhanced protection and storage of soil carbon within soil aggregates and herbicide retention in the bulk soil. As such, employing conservation tillage in more of our nation's agricultural lands is a comprehensive way to mitigate and adapt to continued climate change in a way that benefits agricultural yields and environmental sustainability.

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