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Soil structure and greenhouse gas production differences between row and interrow positions under no-tillage

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ABSTRACT: No-tillage in Brazil is an efficient agricultural system that improves crop productivity whilst controlling erosion caused to the soil by degradation. However, there is some concern regarding soil compaction. Our objective was to determine whether the function of soil structure in sustaining crop growth was dependent on row and interrow positions in long-term no-tillage. We took soil samples from a field in a commercial farm under long-term no-tillage since 1979 on a clayey Oxisol in Southern Brazil. We assessed soil physical quality using the revised Peerlkamp technique and measured bulk density, air-filled porosity and air permeability of intact soil cores. Samples were incubated to assess *in vitro* N_2O and CO_2 production. The soil physical and structural properties showed consistent differences between interrow and row positions, where the properties measured were more favorable. The revised Peerlkamp technique proved as efficient as quantitative parameters in discriminating treatment differences. Overall, soil physical conditions in the interrow were less favourable than in the row. Pore continuity did not vary as regards position. This may explain why row position did not influence *in vitro* N_2O and CO_2 production. Soil physical quality under no-tillage system is enhanced, at least in the short term, by superficial disturbances in the row as a result of the action of the coulters of the no-tillage seeder.

Introduction

No-tillage is an efficient management practice used to control soil erosion in Brazil and is considered to be one of the most important technological innovations for providing agronomic, economic and environmental sustainability in agricultural production systems (Hobbs et al., 2008; Triplett Jr and Dick, 2008). The no-tillage system (NTS) promotes little mechanical disturbance of the soil, which keeps most crop residues on the surface, thereby increasing surface roughness. Under long-term NTS there is growing concern about the negative impact of compaction on the physical quality of the soil, despite the likelihood that the increase in organic matter content may reduce soil compaction (Blanco-Canqui et al., 2009).

Physical properties that indicate dynamic processes related to water and air flow in the soil are more suitable for assessing the quality and physical function of soil under NTS (Cavalieri et al., 2009). Aside from these properties, semi-quantitative indicators such as the Visual Evaluation of Soil Structure (VESS) have been proposed for assessing the soil structural quality holistically (Sq) (Ball et al., 2007; Guimarães et al., 2011, 2013; Giarola et al., 2013; Munkholm et al., 2013) and could potentially be applied to the evaluation of the soil structure in long-term NTS.

Unlike conventional tillage systems (Arshad et al., 1999), soil mobilization in NTS is limited to the plant rows, the intensity of which depends on the type of drill coulter, which is usually equipped with either double discs or furrow openers. Lower soil density (Kaspar et al., 1991), lower soil resistance to penetration (Veiga et al., 2007) and better soil structure (Tormena et al., 2008) have been reported in the row compared to the interrow.

This study was performed to evaluate the hypothesis that crop position (row vs. interrow) influences soil structure under long-term no-tillage and that these changes in soil structure affect soil air permeability and greenhouse gas emission. The objective of this study was to evaluate soil bulk density (Bd), air-filled porosity (*Afp*), Sq through the visual evaluation of soil structure, intrinsic air permeability (*Ka*) as well as *in vitro* production of nitrous oxide (N_2O) and carbon dioxide (CO_2) gases in relation to row and interrow positions under a long-term NTS.

Materials and Methods

Characteristics of the study area

This study was conducted on a commercial grain production farm in Maringá, Northwest Paraná State, Southern Brazil (23°30'40" S, 51°59'48" W), at an average altitude of 454 m and a slope of between 0.03 and 0.08 m m^{-1}. The region has a mesothermal humid subtropical climate, with average annual rainfall between 1,500 and 1,600 mm and average annual temperature between 20 and 22 °C. The Oxisol sampled in this study had a very clayey texture with average contents of 800, 100 and 100 g kg^{-1} of clay, silt and sand, respectively, at 0-20 cm depth. The dominant components of the clay-size fraction (< 2 μm) were kaolinite, aluminium and iron oxides.Therefore, the soil was non expansive.

The NTS was initiated in 1979 with a crop rotation of soybeans (*Glycine max* (L.) Merr.) as summer crop, and black oats (*Avena strigosa* Schreb.) or wheat (*Triticum aestivum* L.) as winter crop. After 1990, the crop rotation included corn (*Zea mays* L.) as summer crop. Corn and soybeans were sown using furrow opener drills while oats and wheat were sown with double disc coulters. The sowing depth varied from 0.05 to 0.07 m. The distance between rows varied from 0.17 m to 0.8 m (Table 1). During the thirty years of cultivation under NTS, lime was broadcast as dolomitic limestone. Fertilizers were applied at sowing, in the row in a separate coulter and at a depth of 0.12 m. Weed and pest control were performed in accordance with the recommendation for each crop. The sowing periods, sowing spacing, sowing density and estimated area occupied of rows and interrows are indicated in Table 1. Tractors, harvester and sprayer traffic was alternated throughout the area, in order to avoid heavy traffic in specific areas and prevent soil compaction.

Sampling

Sampling was conducted at 40 locations along a transect crossing twenty crop rows, approximately thirty days after the sowing of the soybean crop in 2008. At each location (20 in rows and 20 in the adjacent interrow positions) undisturbed soil blocks (0.15 m wide × 0.10 m height × 0.10 m thick) and intact soil cores (50 mm high × 70 mm in diameter) were collected. Blocks were taken from the topsoil through mini-trenches (0.30 m wide × 0.40 m long × 0.30 m deep) using a large spade. The cores were taken in stainless steel rings from the centre of the 0.0-0.10 m layer using an electric sampler that allowed the slow introduction of the volumetric cylinder in the soil without impact during sampling. We sampled this layer because (i) it is the most biologically active zone (Singh, et al. 2008), (ii) it is a possible limiting zone for gas transport (Ball et al., 2007), and (iii) it is the area where soil disturbance occurs under no-tillage.

Field evaluation of soil structural quality

Thirty five days after the soybean sowing, the soil structure quality was evaluated in the soil blocks as described in Ball et al. (2007). A visual soil structural quality (Sq) score was given only for the 0.0-0.1 m deep layer. The evaluation of structural quality was based on the size, strength, porosity and colour of aggregates and results ranged from 1-good to 5-poor structural quality (Ball et al., 2007; Guimarães et al., 2011).

Sample incubations and laboratory gas flux measurements

The intact cores were prepared and stored in the refrigerator at 1 °C to reduce biological activity and to maintain soil structure and were sent to the laboratory. The cores were slowly saturated by capillarity. Once saturated, samples were equilibrated at -10 kPa (field capacity), on a tension table and incubated at 25 °C, a near-surface soil temperature expected in late spring in Brazil. After equilibration, the cores were put into sealed glass Kilner jars (1500 cm^3 - 1 core per jar) containing a three-way gas tap attached to the top of the jar, that was normally left open to the atmosphere. After 24 h, the tap was closed for 1 h, and a 28 mL gas sample was taken by attaching an evacuated glass (glass tubes 1 cm^3 previously subjected to a vacuum) vial to the three way tap, opening the vial and allowing gas to flow from the jar to the vial in response to the change in pressure. An aliquot of gas from the incubation jar was moved to the glass tubes using differential pressure.

Every 1-3 days, aliquots of gas were collected and the concentration of N_2O and CO_2 was determined using gas chromatography. Sampling was done once per day for two days to ensure that any N_2O production as a result of mineralisation of N in the soil during sample preparation had ceased. Then, each intact core was treated with ammonium nitrate solution at an N concentration of 20 kg ha^{-1} by applying 1 mL as drops to the upper surface to assess any priming effect of the fertilizer on N_2O production. Two days later, 4 mL of the same solution of ammonium nitrate was added in the same way at an N rate of 100 kg ha^{-1}.

The concentration of N_2O and CO_2 was determined daily over the nine days following the first fertilizer application in order to detect any production subsequent to the N application which is the period when most N_2O flux associated with fertilizer application is likely to occur (Dobbie et al., 1999). Gas production was calculated from the differences in gas concentration between the start and the end of the closure period, using the geome-

Table 1 – Sowing period, spacing and density for all crops under no-tillage system.

Crop	Sowing period	Sowing spacing, m	Sowing density, plants m^{-2}	Estimated surface area occupied, %		Goal
				Row	Interrrow	
Soybean	spring/summer	0.45	32	60	40	Grain production
Black Oat	fall/winter	0.15	300	60	40	Cover crop and mulching
Wheat	fall/winter	0.17	300	60	40	Grain production
Corn	spring	0.80	6-7	15	85	Grain production
Corn sown off-season	Summer/fall	0.80	6-7	15	85	Grain production

tric properties of the incubation jar and the exposed core surface area.

Intrinsic air permeability (*Ka*), air-filled porosity (*Afp*) and water-filled pore space (*WFPS*) measurements

The intrinsic air permeability (*Ka*) in the undisturbed samples of the cylindrical rings was measured at the end of the experiment. Samples were weighed and placed in an apparatus to quantify the airflow through the samples using the constant heat method of Ball and Schjønning (2002). At the end of the procedure, samples were oven dried at 105 °C for 48 h to determine the soil water content, the soil bulk density (Bd) and to calculate the air-filled porosity (*Afp*) and the water-filled pore space (*WFPS*) using the methods of Ball and Schjønning (2002).

Ka and *Afp* were related by an exponential model (Equation 1), as follows: $Log\ Ka = log\ M + Q\ log\ Afp$, where M and Q are empirical parameters and Q is a pore continuity index. Changes in Q relate to the tortuosity of the pores and surface area. The intercept on the x-axis can be interpreted as an estimate of blocked air-filled pore space which does not contribute to convective flow (Ball et al., 1988). Statistical analysis used the procedures PROC TTEST (row versus interrow analysis) procedures and PROC REG (regression analysis) available in the SAS/STAT software package (Statistical Analysis System, version 8, 2000).

Results

The soil and gas properties are summarized according to location in transect as interrow or row in Figure 1. Although some samples showed a sharp response in gas production to fertilizer addition, most gave small responses. Hence we expressed *in vitro* N_2O and CO_2 production as cumulative over the period after fertilizer application.

Soil physical and structural properties showed a consistent and systematic difference between interrow and row with most properties being more favorable in the rows. The sampling position effect was significant ($p < 0.05$) for all soil physical properties (Table 2). Nev-

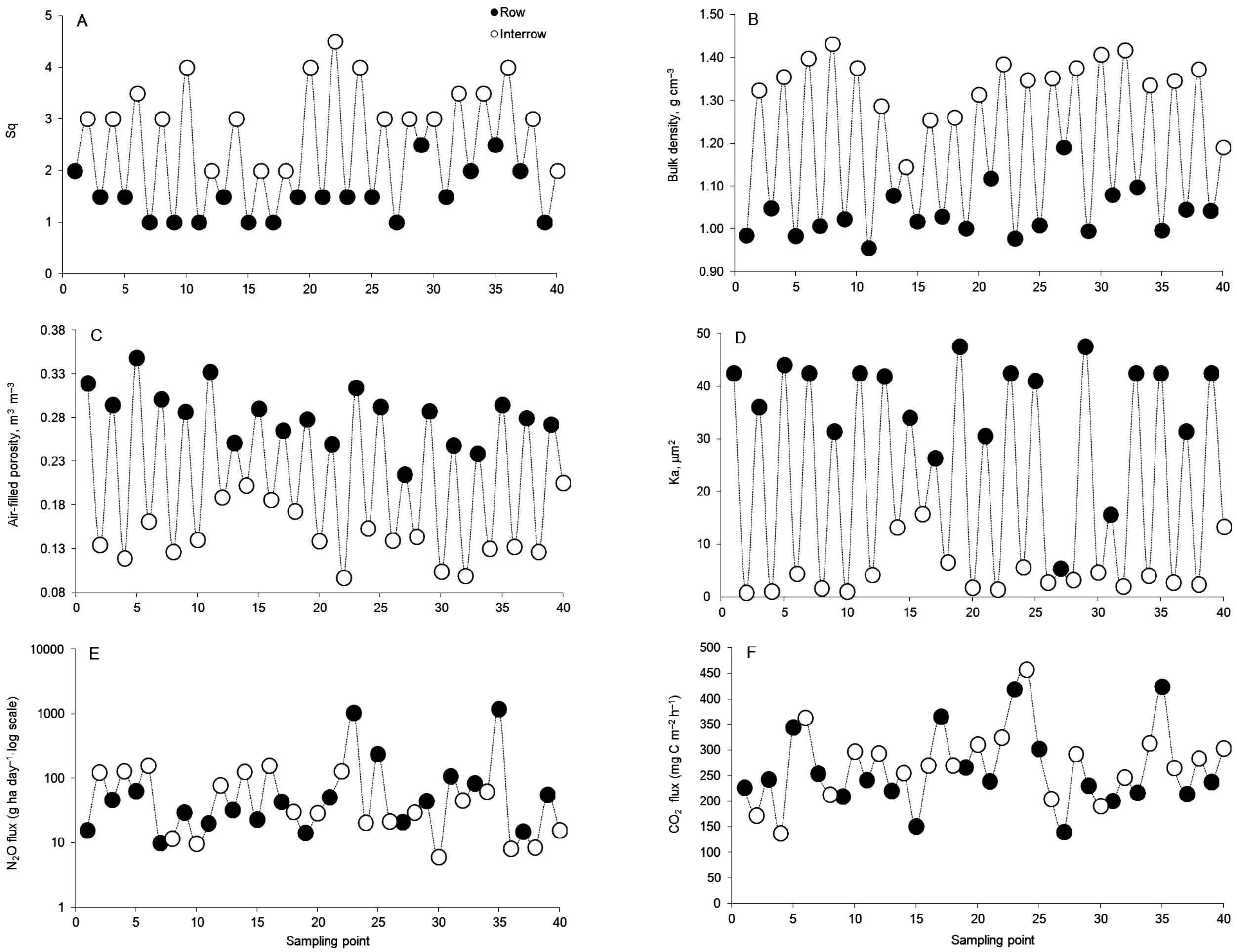

Figure 1 – Variation in soil and gas properties with sampling point along transect according to crop row or interrow position. Sq: Soil structural quality; Ka: Air permeability.

ertheless, some were more sensitive, as judged from the magnitude of the t-value, to the sampling position with Bd > *Afp* > *Ka* > Sq. The variability of Sq and Bd was similar within rows and within interrows. The variability of *Ka* and *Afp* was greater within interrows than within rows.

The mean air permeability in the row was eight times higher than in the interrow (Table 2). The variability of air permeability in the interrow was 3.3 times higher than in the row, whereas the variability of air filled porosity was only twice as high (Table 2). There was no effect ($p < 0.05$) of the treatments on *in vitro* N_2O and CO_2 production. The mean total C and N contents for rows were 2.50 % and 0.21 % and for interrows were 2.47 % and 0.22 %, respectively.

Air permeability and air-filled porosity (Figure 2) were significantly correlated ($p < 0.05$). The interrow and row values form two distinct populations. The regression slopes were not different ($p = 0.95$), and the blocked pores were 0.3 % for rows and 0.4 % for interrows. In rows, N_2O and CO_2 were highly correlated, but not in interrows. In rows there were significant relationships between CO_2 flux and bulk density and air-filled porosity. Soil structural quality was the only soil physical property which approached a significant relationship ($p = 0.09$) with N_2O (Table 3).

Discussion

The Sq score in the rows was better than in the interrows. The mean value of Sq in the interrows (Sq = 3.15) was the boundary between fair and poor (Ball et al., 2007) and showed higher variation within the range of values (2 to 4.5 - Figure 1A), which was clearly observed during analysis. In this situation, 40 % of the observations presented Sq scores higher than 3, 40 % had Sq = 3 (limit of structural quality between good and bad, as Ball et al., 2007) and only 20 % of the samples were not high enough in Sq score considered to require remedial action.

Soils which have Sq score above 3 already require corrective measures to improve the quality of the soil structure for root growth (Ball et al. 2007). On the other hand, in the row position, variation range of the Sq was narrower (1 to 2.5 - Figure 1A) and 90 % had Sq less than or equal to 2. Only in interrow position Sq was significantly ($p < 0.05$) related to soil physical properties (Table 3), because there was a greater range of variation in values than in rows (Table 2). This may be due to heterogeneity in the row caused by root growth and mechanical action by the seeder.

The method was sensitive enough to determine differences in compaction status between soils (Ball et al., 2007; Guimarães et al., 2013), clearly an important factor in the interrows which receive no loosening. The Visual Evaluation of Soil Structure was a rapid test and was shown to be as efficient as the quantitative parameters discriminating between row or interrow positions.

The difference between treatments in bulk density was the most marked (Figure 1B), giving the highest t-value (Table 2). There were four values > 1.40 Mg m^{-3} in the interrows and for the row the highest value found was 1.25 Mg m^{-3}. Blainski et al. (2009) estimated the least limiting water range (LLWR) - a concept of available water that takes into account the influence of aeration and soil resistance to penetration (SR) in addition to soil water potential – and they found that at a bulk density (Bd) of 1.40 Mg m^{-3} the LLWR tends to zero. In other words, the critical bulk density (Bdc) was 1.40 Mg m^{-3}, indicating severe soil physical degradation when Bd > Bdc.

In the interrows, the mean air permeability had greater similarity than that determined by Bavoso et al. (2012) in a clay Typic Hapludox, but higher than in a sandy clay loam Typic Hapludox (Silveira Júnior et al., 2012) in the same soil water potential (-10 kPa) and management. There were two values below 1 µm² (Figure 1D), which is the value considered by Ball et al. (1988) to represent pore blockage of the system, because when *Ka* = 1 µm² (log *Ka* = 0) the pores were blocked and would not be part of the convective air transport (McQueen & Shepherd, 2002). This low *Ka* is related to the action of mechanical stresses determined by the intensive traffic of machinery on wet soil conditions that reduce air permeability as a consequence of reduced macroporosity (Dörner and Horn, 2009). On the other hand, the mean *Ka* (Table 2) was about three times higher in the rows than that measured by Bavoso et al. (2012), indicating that mobilization provoked by the implement used for seeding (furrow openers) promoted the aeration of the soil at specific areas.

Table 2 – Means and associated statistics for all soil and gases properties measured on undisturbed samples.

Statistical parameters	Sq		Bd, Mg m^{-3}		*Ka*, µm²		*Afp*, m^3 m^{-3}		CO_2 flux, mg C m^{-2} h^{-1}		N_2O flux, µg N m^{-2} h^{-1}, log scale	
	IR	R	IR	R	IR	R	IR	R	IR	R	IR	R
Mean	3.15	1.5	1.33	1.03	4.56	36.48	0.145	0.283	273.45	257.46	3.567	3.927
SD	0.74	0.49	0.07	0.06	4.39	10.74	0.032	0.033	70.64	77.363	1.114	1.302
CV (%)	24	32	6	5	96	29	22	11	26	30	31	33
Min	2	1	1.14	0.96	0.73	5.42	0.097	0.215	138.04	139.78	1.779	2.298
Max	4.5	2.5	1.43	1.19	15.66	47.53	0.205	0.348	457.47	424.07	5.055	7.081
t value	-8.29		-14.35		12.30		13.50		-0.68		0.94	
P (t)	< 0.0001		< 0.0001		< 0.0001		< 0.0001		0.49		0.35	

IR: Interrow; R: Row; Sq: Soil structural quality; Bd: Bulk density; *Ka*: Air permeability; *Afp*: air-filled porosity.

Table 3 – Pearson's Correlation Coefficient for soil and gases properties. Probability values in brackets.

	Bd	*Ka*	*Afp*	CO_2	N_2O
			Row		
Sq	-0.126	0.361	0.099	0.257	0.389
	(0.59)	(0.12)	(0.68)	(0.27)	(0.09)
Bd		-0.722	-0.913	-0.528	-0.269
		(<.0001)	(<.0001)	(0.017)	(0.25)
Ka			0.624	0.402	0.189
			(0.003)	(0.079)	(0.43)
Afp				0.478	0.213
				(0.032)	(0.37)
CO_2					0.747
					(0.0002)
			Interrow		
Sq	0.520	-0.565	-0.629	0.320	-0.084
	(0.019)	(0.009)	(0.003)	(0.17)	(0.73)
Bd		-0.786	-0.839	-0.054	-0.235
		(<.0001)	(<.0001)	(0.82)	(0.32)
Ka			0.786	0.177	0.262
			(<.0001)	(0.45)	(0.26)
Afp				0.268	0.198
				(0.25)	(0.40)
CO_2					-0.071
					(0.77)

Sq: Soil structural quality; Bd: Bulk density; *Ka*: air permeability; *Afp*: air-filled porosity.

Air-filled porosity in the row was the double of that observed in the interrow. Nevertheless, there were only two values lower than 10 %, indicating that air-filled porosity and, possibly, soil aeration were mostly favorable within the rows. Air-filled porosity values between 0.05 and 0.15 (m^3 m^{-3}) can be used as critical limits (Chan, 2002); below this range there is insufficient aeration for root growth. In this case, we observed mean values of 0.145 m^3 m^{-3}, indicating root growth could be constrained by the low aeration.

The favorable, though variable, soil physical conditions within rows were due to the loosening action of the chisel coulters of the no-tillage seeder. These penetrate up to 0.12 m depth, giving localized tillage. The coulter acts like a small tine cultivator to 0.12 m depth. This action helps to alleviate surface soil compaction (Veiga et al., 2007).

Despite the marked soil physical differences between row and interrow there was no effect on *in vitro* CO_2 and N_2O production. The overall magnitude of the *in vitro* N_2O production in this soil was small, though further research is needed on these soils to quantify possible emissions. Low fluxes after fertilizer application are usually associated with satisfactory aeration (Dobbie et al., 1999). Our soil physical data gave no evidence of poor aeration conditions likely to result in denitrification. *In vitro* CO_2 productions were typical for soils with these intrinsic properties (La Scala et al., 2001). The two locations with highest *in vitro* N_2O production were from row positions 23 and 35. *In vitro* CO_2 production was also high at these locations. These positions showed no unusual soil physical properties so that the high fluxes were likely caused by crop residues forming hot spots of biological activity in soil conditions favoring soil respiration.

The blocked pores derived from the relationship between air permeability and air-filled porosity had low values compared to those given by Ball et al. (1988), Schjønning et al. (2002) and Dorner and Horn (2009). In addition, the value of the pore continuity index is also low (Figure 2) compared to those given by Ball et al. (1988) and Schjønning et al. (2002), but it indicates favorable pore continuity. Thus, despite the disturbance of the soil within the row, the pore continuity was maintained. Furthermore, the low blocked porosity indicates that the favourable soil porosity conditions associated with microaggregation typical of the Oxisol (Volland-Tuduri et al., 2005) were preserved or recovered by long-term no-tillage. Hence, the configuration of the pore space in the soil of interrows and rows is similar.

The main difference between rows and interrows can be inferred from the differences in air permeability as a greater size (pore radius) and number of conducting air-filled pores in the rows than in the interrows. Nevertheless, pore continuity was similar in interrow and row soil and this may have made up for the poorer soil physical conditions in the interrows and may be the reason for the lack of difference between them in N_2O and CO_2 flux. Despite overall soil physical conditions in the interrow being less favorable than in the row, they are adequate to enable dynamic properties such as aeration to function, which agrees with the conclusion of Cavalieri et al. (2009).

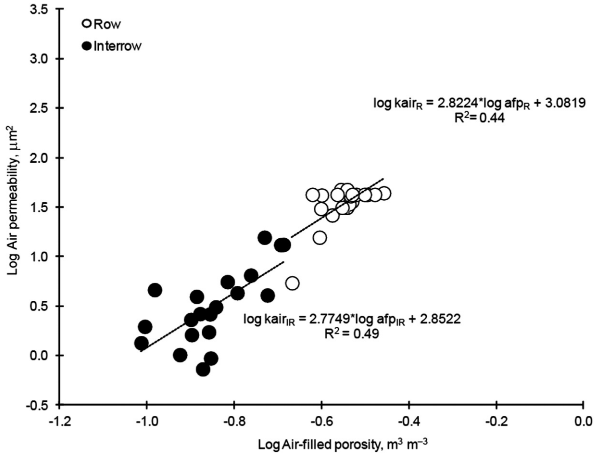

Figure 2 – Relationship between intrinsic air permeability and air-filled porosity. The slope equals the pore continuity index, N.

Conclusions

Soil physical parameters were more favorable in the row position. However, no difference in *in vitro* CO_2 or N_2O production was detected between positions, possibly because of the similar pore continuity in both soils maintaining satisfactory aeration status. Soil physical quality under no-tillage system is enhanced, at least in the short term, by the superficial disturbance in the plant rows provided by the action of the coulters of the no-till seeder and roots.

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