Soil compaction response to wheel traffic in the Rolling Pampas region of Argentina

Respuesta de la compactación del suelo al tráfico de ruedas en la Región de la Pampa ondulada de Argentina

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Abstract

The present work shows the effects of the different agricultural wheels traffic on the physical properties of a typical Argiudol soil worked under a no-tillage cropping system. Soil compaction produced by traffic was quantified through a series of parameters. These parameters were: a) cone index, b) rut depth and c) soil water content at the traffic moment. A grain chaser, a sprayer, a combine harvester and a tractor equipped with commonly used wheels were tested in the study area. The main results obtained showed that the tyres with the highest inflation pressure and tyre ground pressures produced the highest values of cone index and rut depth. A typical Argiudol soilis not able to constrain topsoil and subsoil compaction when wheeled by tyres with ground pressures greater than 77.6 kPa. This occurs when this soil is worked under a continuous no-tillage cropping system.

Keywords
tyre inflation pressure • cone index • soil bearing capacity

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Resumen

En el presente trabajo se muestran los efectos del tránsito de diferentes ruedas agrícolas sobre las propiedades físicas de un suelo Argiudol Típico trabajado bajo el sistema de no-labranza. La compactación del suelo producida por el tráfico se cuantificó a través de los parámetros: a) índice de cono, b) profundidad de huella y c) contenido de agua del suelo al momento del tránsito. Se ensayaron carro de granos, cosechadora, pulverizadora y tractor equipados con rodados de uso generalizado en la zona productiva bajo estudio. Los principales resultados obtenidos demostraron que los neumáticos con mayor presión de inflado y presión en el área de contacto rueda/suelo produjeron los mayores valores de índice de cono y profundidad de huella. El suelo Argiudol típico trabajado en forma continua bajo no-labranza no puede limitar la compactación superficial y subsuperficial del suelo cuando es transitado por ruedas con presiones en el área de contacto rueda/suelo mayores a 77.6 kPa.

Palabras clave

presión de inflado • índice de cono • capacidad portante del suelo

Introduction

According to the European Soil Framework Directive (2006), compaction, in addition to water and wind erosion, is one of the main causes of soil degradation. It has been estimated that more than half of the world's eroded area is caused by soil compaction and soil deformation. As a matter of fact, soil compaction and soil deformation are produced by incorrect soil management. Traffic compaction has adverse effects on the physical, chemical and biological properties of soil. This affects important soil processes and functions that govern the crop productivity (2).

Soil compaction causes a reduction in root growth and yield in many crops. Botta *et al.* (2004) applied 4 Mg tractor traffic in a field where a wheat-soybean double cropping rotation under no-tillage had been practised for seven years. Traffic was applied at intensities of 60 to 180 Mg km ha^{-1}. This treatment caused soil compaction up to 600 mm depth. As a result, there was a decrease in yield of the following soybean crop from 9.8% to 38%, respectively. Besides, Canarache *et al*. (1984) found that for each 1 kg/m^3 increase in bulk density in Romanian soils, a decrease in maize grain yields was 18% relative to the yield in a non-compacted plot.

According to Raper (2005), soil deterioration produced by agricultural traffic can sometimes be visible above-ground as soil deformation or it can be hidden below-ground. In either case, agricultural traffic can reduce crop production by causing a compacted soil condition that is not compatible with plant growth. Traffic-induced compaction in the subsoil (below 200 mm in our case) tends to be cumulative. This is because standard tillage operations are rarely performed at depths greater than about 25-30 cm (6, 17).

Compaction is caused by the high wheel loads and tyre ground pressures exerted on the soil by the tires of machinery used in no-tillage crop operations. Special emphasis should be placed on the impact of these operations when performed on wet clay soils or with high tire inflation pressure (between 140 and 218 kPa) (10).

It is difficult to generalise, globally, however there is a growing knowledge base that random traffic operations with heavy machinery on moist soil causes soil compaction specifically, and more generally, reductions in water use and fertiliser efficiencies and crop productivity, and off-site environmental problems particularly from increased runoff (26).

Threadgill (1982) noted that soils with a CI >1.5 MPa reduced root growth. In this regard, when soils are compacted with CI values higher than 2 MPa, the roots of most annual crops practically stop growing (7).

There are a number of techniques commonly utilized for the control and management of topsoil and subsoil compaction. These techniques are subsoiling and chiseling, controlled traffic farming (CTF), seasonal controlled traffic farming (SCTF) and axle load reduction (2). Deep soil compaction remediation can prove impractical, and often uneconomical, at depths greater than about 400-mm (9, 15, 18, 24, 25).

Note that permanent traffic lanes represent full adoption of the CTF. On the other hand, the SCTF refers to temporary tracks, where affected areas may be targeted for post-harvest remediation. Regarding the SCTF, Vermeulen and Mosquera (2009) found that the mean total and air-filled porosity at 10 kPa of topsoil water matric pressure increased on average from 0.468 to 0.492 and from 0.132 to 0.166, respectively. This was observed in comparison to the random traffic system for crops grown in a field study between 2002 and 2005. They also found that crop yields increased significantly by 31% in green peas in 2002, by 15% in spinach in 2004 and by 10% in planted onion sets in 2005. On the other hand, no differences were observed in carrot and sown onion when the SCTF system was used instead of the random traffic system.

The work presents two objectives. The first objective was to evaluate the effect of wheel traffic on the soil physical properties of a typical Argiudol soil in the Rolling Pampas region of Argentina. The second objective was to study the traffic layout in different agricultural tasks to reduce compaction in a soil under a continuous no-tillage cropping system. Our hypothesis was that, in a soil under a continuous no-tillage cropping system, compaction mitigation may be achieved by operating with low-loads, low contact pressure from tyres and reducing the trampled area.

Materials and methods

The site

The experiment was conducted in the east of the Rolling Pampa region, Buenos Aires State, Argentina. The soil is a typical Argiudol (22) worked under a no-tillage system. The soil physical and mechanical properties are given in table 1.

Table 1. Typical Argiudol soil profile characteristics.

Tabla 1. Características del perfil del suelo Argiudol típico.

	Ap	A12	B1	B21t	B22t	B23t	B3	Cca
Depth (mm)	5-10	16-25	25 -35	35 - 55	55 - 80	80 - 110	110-150	150 - 220
Organic Carbon (%)	2.05	1.44	0.95	0.61	0.55	0.32	0.20	0.11
Total nitrogen (%)	0.23	0.132	0.102	0.081	0.072	0.053	0.031	-----------
C/N ratio	8.9	10	9	8	8	6	6	-----------
Clay (<2 µ)	20.1	24.8	27.9	34.2	46.4	32.0	22.0	14.9
Silt (2-20 µ)	33.1	34.6	29.5	28.1	20.7	30.0	31.8	29.9
Silt (2-50µ)	75.6	70.8	67.2	61.3	50.0	63.0	72.7	79.9
Fine sand (100-250t µ)	0.3	0.2	0.3	0.4	0.4	0.4	0.5	0,4
Equvalent moisture (%)	26.6	28.5	26.8	28.7	35.2	31.9	27.0	23.5
pH	5.4	5.3	5.5	5.5	5.8	6.0	6.0	7.5
pH in H20 (1: 2.5)	5.8	5.8	6.0	6.2	6.5	6.4	6.4	7.9
Cation exchange (m.e. 100g)								
Ca^{2+}	11.4	12.7	12.0	13.8	18.3	17.2	16.5	-----------
Mg^{2+}	2.9	2.5	3.1	4.5	6.5	6.4	3.8	-----------
Na^{+}	0.2	0.1	0.2	01	0.2	0.2	0.3	0.5
K^{+}	1.4	1.0	0.9	1.3	2.3	2.4	2.3	2.4

Treatments

We performed five treatments. One of these treatments was used as a control with no traffic. The remaining four treatments were carried out with machines that had different tyre ground pressures. The modification of each treatment is determined by the agricultural machine and the tyre to be used respectively. Description of the machinery used is given in table 2 (page 112). The real work speed was calculated with the distance / time equation for each labour. The time the equipment took to travel 75 m of each plot was recorded.

Table 2. Characteristics of the machinery used in the trial.
Tabla 2. Características de la maquinaria usada en el ensayo.

Tractor FWA		Grain chaser (Two axle and single wheels)	
Engine power (CV/kW)	145/106.7	Front tyres	24.5 R 32
Front tyres	16.9 R 26	Rear tyres	24.5 R 32
Rear tyres	24.5 R 32	Inflation pressure, front tyre (kPa)	120
Inflation pressure, front tyre (kPa)	70	Inflation pressure, rear tyre (kPa)	120
Inflation pressure, rear tyre (kPa)	65	Overall weight loaded (kN)	196
Overall weight (kN)	79.80	Front weight (kN)	98
Front weight (kN)	31.75	Rear weight (kN)	98
Rear weight (kN)	48.05	Static load per front wheel (kN)	49
Static load per front wheel (kN)	15.875	Static load per rear wheel (kN)	49
Static load per rear wheel (kN)	24.025	Mean ground pressure per for front tyre (kPa)	77.6
Mean ground pressure per for front tyre (kPa)	37.63	Mean ground pressure per rear tyre (kPa)	78.7
Mean ground pressure per rear tyre (kPa)	40.02		
Distance between the tyres of the tractor and tyres of the grain chaser (mm)	3.380		
Combine Harvester		**Sprayer**	
Engine power (CV/kW)	255/187	Engine power (CV/kW)	142/104
Front tyres	600/70 R 30	Front tyres	12.4-36
Front tyres inflation pressure (kPa)	140	Front tyres inflation pressure (kPa)	285
Rear tyres	11.25 – 24	Rear tyres	12.4-36
Rear tyres inflation pressure (kPa)	145	Rear tyres inflation pressure (kPa)	285
Total weight loaded (kN)	152.5	Total weight loaded (kN)	108.7
Front axle weight (kN)	103.7	Front axle weight (kN)	43.48
Rear axle weight (kN)	48.8	Rear axle weight (kN)	65.22
Static load per front wheel (kN)	51.85	Static load per front wheel (kN)	21.74
Static load per rear wheel (kN)	24.4	Static load per rear wheel (kN)	32.61
Mean ground pressure per front tyre kPa)	135	Mean ground pressure per front tyre kPa)	233
Mean ground pressure per rear tyre (kPa)	198	Mean ground pressure per rear tyre (kPa)	254
Hedaer width (m)	7	Sprayer boom width (m)	21

The treatments were settled in plots of 100 m long by 20 m wide (2000 m^2), in four completely randomized replications plots (figure 1, page 113). A buffer zone of 10 m between plots was established according to the proposal of Maineri (2020).

The mean ground contact pressure (GCP) of the machines was measured with a Tekscan device. Tyre inflation pressures were adjusted according to the tyre manufacturers' recommendations for the load and the operation speed. Note that the soil water content (SWC) at the traffic moment was near but below the field capacity.

Parameters monitored

Cone index (CI), soil water content (SWC) and rut depth (RD) were measured on the same day as the traffic treatments were applied. The parameters (CI, SWC and RD) were measured along the central 50 m of each plot. The CI was measured with a recording penetrometer (4) and the procedure according to ASABE (2013). The average of 25 samples was taken as the datum for each plot at a depth range of 0–450 mm, measured at 25 mm depth intervals. The SWC was estimated according to Botta *et al*. (2002). The RD was measured using a profile meter consisting of a set of vertical metal rods of 700 mm long and 5 mm in diameter. These rods were spaced at 25 mm horizontal intervals, sliding through holes in a 1-m long iron bar. The bar was placed across the removed soil perpendicular to the direction of travel and the rods were positioned to conform to the shape of the depression. The removed area was calculated as the average depth of 20 reads on the 1-m bar.

Explanatory variables

The trampled area (TA) by agricultural machinery was determined using a PCS-215 Pentax total station. Finally, the maximum bulk density (BD) and the critical soil water content (SWC) were determined according to the standard Proctor method (5) described by Botta *et al.* (2012).

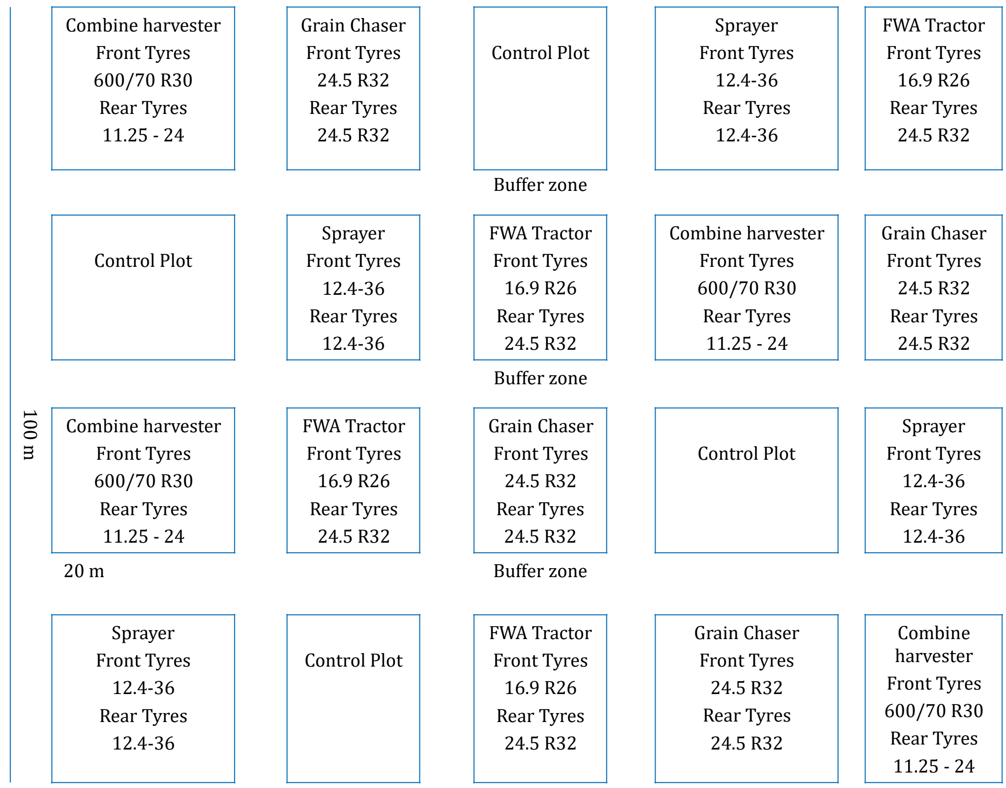

Figure 1. Experimental design. / **Figura 1.** Diseño experimental.

Statistical analyses

Statistical analyses were performed by the Statgraf program 7.1. An analysis of variance (ANOVA) was carried out and means were analyzed by Duncan's multiple range test. A priori we confirmed that the soil data followed a normal distribution, according to the Shapiro-Wilk test. When checking the normality of the deviations of each data with respect to the average of the respective treatment, the normality of the same was assumed (13).

Results and discussion

Soil water content and Cone index

The differences in the soil water content (SWC) were generally not significant between the different depth intervals on the day the traffic treatments were imposed on each sample (table 3). Therefore, the variations in CI in depth were not due to the SWC. This suggested that the cone index was a reliable indicator of the soil compaction degree as a function of the traffic treatment.

Table 3. Soil water content (w/w) at the traffic moment.

Tabla 3. Contenido de agua del suelo (m/m) al momento del tráfico.

Soil water content (w/w)	
Depth range levels (mm)	
0-150	21.1 ± 1.27 a
150-300	22.3 ± 1.24 a
300-450	22.9 ± 1.33 a

Average values ± standard deviation (n = 25).
Values with different letters are significantly different at each depth (P<0.01 Duncan's multiple range test).

Valores medios ± desviación estándar (n = 25).
Los valores con letras diferentes son significativamente diferentes para cada profundidad (P <0,01 Prueba de rango múltiple de Duncan).

According to table 3 (page 113), the SWC at the traffic moment was 21.1% in the topsoil (0–150 mm), 22.3% at 150–300 mm and 22.9% at 300– 450 mm. According to this, the SWC values at the time of testing were 0.9 points lower than the Proctor value (22.0%) in the 0 to 150 mm depth range. The SWC values were also 1.6 points lower than the Proctor value (23.9%) in the 150 to 300 mm depth range and 0.5 points minor (23.4%) in the 300 to 450 mm depth range respectively. From the mentioned Proctor values, it can be inferred that the SWC, at the traffic moment, was close to the value that can produce maximum soil compaction. This situation is very important when analyzing the compaction results due to traffic because it was the worst moment to carry out the traffic. However, these are normal values of soil water content when the farmers perform most of the agricultural work (7).

It is important to note that the typical tillage depths in Argentina are approximately 200 mm. Therefore, the Ap horizon is considered, in this experiment, 0–200 mm as the topsoil layer. The subsoil can be defined as the soil below the tillage layer (6).

The cone index data gave a clear indication of the initial soil condition in each treatment (table 4). The CI values reached their maximum at 200 mm depth (≈2653 kPa) in the topsoil of the control plot. On the other hand, in the subsoil the maximum CI value was found at 450 mm depth (≈3247 kPa).

Table 4. Average (n = 25) cone index values (kPa) for the traffic treatments.

Tabla 4. Valores medios (n = 25) de índice de cono (kPa) para los tratamientos de tráfico.

Values with different letters (horizontally) are significantly different at each depth (P<0.01 Duncan's multiple range test).

Los valores con letras diferentes (horizontalmente) son significativamente diferentes para cada profundidad (P <0,01 Prueba de rango múltiple de Duncan).

Depth (mm)	Control plot (unloosened soil)	FWA Tractor	Grain chaser	Combine harvester	Sprayer
Topsoil (0 to 200 mm)					
0	1507 a	1723 b	1888 c	2200 d	2433 e
25	1682 a	1801 b	1980 c	2256 d	2525 e
50	1790 a	1904 b	2150 c	2334 d	2622 e
75	1880 a	2000 b	2187 c	2369 d	2740 e
100	2132 a	2250 b	2530 c	2698 d	2888 e
125	2167 a	2360 b	2563 c	2793 d	2951 e
150	2250 a	2450 b	2610 c	2804 d	2983 e
175	2369 a	2556 b	2690 c	2841 d	2990 e
200	2653 a	2700 a	2802 c	2959 d	3190 e
Subsoil (> 200 mm)					
225	2800 a	2900 a	3400 c	3234 b	3200 b
250	2901 a	2910 a	3457 c	3272 b	3196 b
275	2920 a	2940 a	3560 c	3230 b	3180 b
300	2956 a	2990 a	3601 c	3241 b	3200 b
325	2980 a	3010 a	3656 c	3287 b	3210 b
350	3001 a	3078 a	3678 c	3352 b	3265 b
375	3100 a	3140 a	3689 c	3390 b	3300 b
400	3145 a	3195 a	3699 c	3410 b	3309 b
425	3201 a	3233 a	3710 c	3429 b	3321 b
450	3247 a	3276 a	3745 c	3503 b	3400 b

These CI values in the control plot could tend to retard root growth in situations of low soil water content. However, there could also be an improvement in the soil bearing capacity that could moderate, together with the crop harvest residue on the soil surface, the negative effects of the agricultural traffic.

Besides, the treatments with the highest average ground pressure (combine harvester (> 135 kPa) and sprayer (> 233)) caused CI values exceeding 2000 kPa from the 0 mm depth level. Botta *et al.* (2018b) suggested that this value is a limitation, not only of the seed emergence, but also for the root development. It is important to mention that Threadgill (1982) indicates that CI values above 1500 kPa decrease root development, while CI values of 2100 to 2500 kPa can stop root growth.

For these treatments (the combine harvester and the sprayer), the CI values were higher than 2500 KPa in the subsoil, (300 mm to 450 mm), denoting over-compaction. Also for these treatments, the CI exceeded the critical soil strength values, above which root growth and expansion are significantly affected (*e.g.,* 11, 14, 18, 19).

According to Botta *et al.* (2019), subsoil compaction is due to several factors. These factors are the high wheel load, the tyre ground pressure, and the machinery traffic intensity used for crop protection and harvest operations, rather than for seeding. Special emphasis should be placed on the impact of these operations when performed on wet clayey soils or with high tyres inflation pressure (between 140 and 218 kPa).The induced soil compaction within this layer is cumulative, since no conventional tillage is performed at that depth.

Finally, the FWA tractor showed significant differences (in CI values) with respect to the control plot up to a depth of 175 mm (P<0.01). This indicated an increased subsoil carrying capacity compared to topsoil.

The rut depth measurements were significantly different for the sprayer machine and the combine harvester compared to the FWA tractor and the grain chaser (P<0.01). The sprayer and the combine harvester showed significantly higher RD values than the FWA tractor and the grain chaser. This was due to the high tyre ground pressure, being 23.7 and 20.1 mm for the sprayer and the combine harvester respectively (table 5). It should be noted that, despite the high tyre ground pressures values, the RD did not exceed 25 mm in any treatment. This probably occurred because that CI in the control plot already exceeded 2132 kPa at 100 mm depth. This indicated the high level of previous compaction it had due to the application of a continuous no-tillage cropping.

Table 5. Average values (n = 20) of rut depth (mm) in the four traffic treatments.

Tabla 5. Valores medios (n = 20) de profundidad de huella (mm) en los cuatro tratamientos de tráfico.

Sprayer	Combine Harvester	FWA Tractor	Grain Chaser
23.7 a	20.1 a	12.1 b	15.7 c

Values with different letters (horizontally) are significantly different at each depth (P<0.01) Duncan's multiple range test).

Los valores con letras diferentes (horizontalmente) son significativamente diferentes para cada profundidad (P <0,01 Prueba de rango múltiple de Duncan).

As for the RD, Table 5 shows that the sprayer rut depth is 12.98% greater than the combine harvester rut depth. This should be taken into account even though there are no significant differences between the combine harvester rut depth and the sprayer rut depth. The results are in agreement with the results of Botta *et al*. (2019) and Raper (2005). These autors also indicated that the soil surface was the most vulnerable layer to both compression and displacement from the passage of the agricultural machinery.

In addition, there was a clear correlation (statistically significant) between RD and soil compaction (R^2 values were between 0.90 and 0.96 for CI) in the deeper subsoil (200 to 450 mm) for the combine harvester. This correlation was not clear (R^2 values were between 0.04 and 0.07 for CI) [P <0.01]) in the case of the grain chaser. In this treatment, the mean values of GCP per tyre and wheel load did not exceed 78.7 kPa and 49 kN, respectively.

The measurements of TA (m^2 ha^{-1}) were significantly different for all traffic treatments (table 6, page 116). The smallest TA corresponds to the sprayer. This is easy to understand due to the wide case of the tyre that these kinds of machine use. However, despite this, it is important to remember that the tyre ground pressure RD was the highest for this machine. The average RD value was 23.7 mm. From this it can be noted that the tyre ground pressure exceeded 200 kPa in both axes.

Table 6. Average values (n = 20) of trampled area (m^2 ha^{-1}) in the four traffic treatments.
Tabla 6. Valores medios (n = 20) de área pisada (m^2 ha^{-1}) en los cuatro tratamientos de tráfico.

Sprayer	Combine Harvester	FWA Tractor *	Tractor and Grain Chaser
300.1 a	1713.6 c	1777.3 d	373.3 b

Values with different letters (horizontally) are significantly different at each depth (P<0.01) Duncan's multiple range test). * FWA Tractor and planter wheeled on the same track.

Los valores con letras diferentes (horizontalmente) son significativamente diferentes para cada profundidad (P <0,01 Prueba de rango múltiple de Duncan).

In the case of the FWA tractor, it should be noted that it produced a high trampled area per hectare. The value shown in table 6 seems high. Nevertheless, the trampled area produced by this tractor when it traffics on the same track as the grain planter caused the trampled area to be masked in that of the grain planter. This is very important for the annual traffic planning, as well as the track alignment of the machinery used as far as possible.

Finally, it was shown that when the machinery load increases on soils with high bearing capacity (soils under a long-term no-tillage system), the subsoil compaction problems increase. Hence, these data support the hypothesis. This hypothesis includes: In soils under a continuous no-tillage system, compaction mitigation may be achieved by operating with low-loads, low contact pressure from tyres and reducing the trampled area.

Conclusions

Given the experimental conditions of this study, the following conclusions can be drawn:

1) The area trampled by the agricultural machinery can be reduced by making a previous planning of the traffic as well as an adequate regulation of the wheel track width. In addition, track alignment of the agricultural machines can alleviate the compaction produced by the passage of the wheels with high load.

2) Soil under a no-tillage system does not limit topsoil and subsoil compaction when wheeled by tyres with ground pressures greater than 77.6 kPa.

3) Also, in relation to the machinery weight, it was established that agricultural machinery with a minimum weight of 79.8 kN (FWA tractor) can produce subsoil compaction with a single pass.

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