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SHORT-TERM AND LONG-TERM EFFECTS OF FIELD TRAFFIC-INDUCED SOIL COMPACTION UNDER PANNONIAN CONDITIONS

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ABSTRACT

Soil compaction induced by in-field traffic affects key soil functions and plant growth. In the context of the SoilCompaC project (EJP SOIL), a three-factorial field experiment was established in Lower Austria to investigate the effects of field traffic (slurry tanker-tractor combination wheeling with different loads in spring), soil tillage for cover crops (ploughing, cultivating, no-tillage) and cover crop mixtures (deep rooted, shallow rooted, no cover crop) on soil physical parameters and grain maize yield. The results of the experiment on short-term effects show that the measured indicators (track depth, soil penetration resistance, bulk density, crop yield) detect soil compaction well. Overall, the field experiment results show that the testing factor wheel load affects the measured parameters more than the factors tillage for cover crops and cover crop mixtures. The headlands of arable cropping fields are evident sites for long term soil compaction. The higher field traffic frequency with higher wheel load in the headland resulted in higher soil penetration resistance in the subsoil. Further soil physical parameters (saturated hydraulic conductivity, bulk density, air permeability) respond in the compacted headland – especially in the subsoil. This site-specific result indicates that the compacted soil in the headland accumulated organic carbon and nitrogen in the soil. This could be explained by a reduced decomposition of soil organic matter due to mitigated air permeability. The conclusion of this study is that physical soil protection with its technical and agronomic measures is a keystone in knowledge-based cropping (smart farming).

Keywords: *Wheel load, Cover crop, Soil physical parameters, Headland, Earthworms, Crop yield, Soil organic carbon.*

INTRODUCTION

Soil compaction induced by in-field traffic affects key soil functions and plant growth. Soil compaction is a serious global problem and a major cause of inadequate rooting and poor yields of crops around the worldwide (Correa et al., 2019). Field traffic is responsible for soil compaction with severe impacts on the soil functioning and negative consequences for crop production. The published report from the mission board for soil health and food, "Caring for soil is caring for life" (European Commission, 2020) estimates that the area of land failing soil health due to compaction is 23-33%. Agricultural soil provides a wide diversity of ecological services (e.g., root growth, water movement, aeration) that are directly influenced by the physical properties of soils (Lamandé et al., 2018). Short term effects of soil compaction are visible in deformed soil (= track depths caused by tires and rubber tracks in the field), reduced rooting, and lowered crop yield. Besides physical properties, also the soil carbon and nitrogen cycles are affected by soil compaction (Nawaz et al., 2013). Long-term experiments on soil compaction are barely available to examine the long-term effects. It is well known that the headlands of arable fields are hot spots for compaction in fields due to the higher vehicle traffic frequency and increased wheel loads. The compaction in headlands alters the soil´s mechanical and hydraulic properties, leading to changes in key soil functions such as water and air flow, as well as carbon and nitrogen stocks, ultimately impacting plant growth and yields (Correa et al., 2019; Ward et al., 2021)

Aim of the research is to investigate the short-term effects and long-term effects of soil compaction based on experimental trials in the pedo-climatic zone of Pannonian with a calcaric chernozem of alluvial origin. A three factorial field experiment was established to assess the short-term effects of field traffic, soil tillage for cover crops (ploughing, cultivating, no-tillage) and cover crop mixture (deep rooted, shallow rooted, and no cover crop) on soil physical parameters, earthworm abundance and crop yield in the year 2024. The long-term effects of soil compaction were investigated in an arable field near the previously mentioned experiment to compare the soil physical parameters and soil organic carbon stocks in headland (compacted) and in-field (non-compacted) in the year 2023.

MATERIALS AND METHODS

The short-term effect experiment was conducted in the third year of a long-term field trial at the Experimental Farm Groß-Enzersdorf on a calcaric chernozem under Pannonian climate. The soil (0–30 cm) is a silty loam (19.9% clay, 44.1% silt, 36.1% sand) with 16.3 g kg^{-1} organic carbon. In 2024, the mean temperature was 12.9 °C and the annual precipitation was 668 mm. Monthly precipitation and mean temperatures were: January 37 mm / 3.2 °C, February 11 mm / 9.4 °C, March 64 mm / 10.0 °C, April 50 mm / 13.3 °C, May 67 mm / 16.9 °C, June 93 mm / 20.3 °C, July 23 mm / 22.2 °C, August 43 mm / 22.6 °C, and September 224 mm / 16.5 °C. During the growing season of maize (April 29 – September 5), rainfall totaled 226 mm (Geosphere Austria, 2025). Due to low spring moisture, 40 mm irrigation was applied on April 9, two days before traffic treatment. A split-plot design with three replications was used. Main plots included three tillage treatments for cover crops: mouldboard plough (MP), cultivator (CT), and no tillage (NT). Each was subdivided into three cover crop treatments: deep-rooted (CCd), shallow-rooted (CCs), and no cover (CCno). CCs (45 kg ha^{-1}) included pea – *Pisum sativum*, flaxseed – *Linum usitatissimum L.* and phacelia – *Phacelia tanacetifolia*; CCd (33 kg ha^{-1}) included fodder radish – *Raphanus sativus L. oleifromis Pers.*, safflower thistle – *Carthamus tinctorius* and ramtil – *Guizotia abyssinica*. Tillage plots measured 34 × 27 m; subplots for the cover crop treatment were 34 × 9 m.

Defined mechanical soil stress was applied on April 11, 2024, using a tractor–slurry tanker combination (10 m^3, pendulum tandem axle) at an average soil moisture of 27% (v/v). Tire pressure was set to 300 kPa for the tractor and 400 kPa for the tanker. Three load levels were tested: Low (m_{Total}=10335 kg; wheel-load$_{max}$=18 kN), High (m_{Total}=15825 kg; wheel-load$_{max}$=26 kN), and High-double (two passes with High).

After winter wheat harvest, the field was disked, and treatment-specific tillage and cover crop sowing took place on August 3, 2023. Cover crops were terminated with herbicide on April 9, 2024, following compaction. Maize (P9610, FAO 370) was sown directly into the dead mulch on April 29 at 76000 seeds ha^{-1} using a precision planter (75 cm row spacing). Six maize rows were planted around the trial area as a buffer. Fertilization included 100 kg N ha^{-1} as stabilized urea. Harvest took place on September 5, 2024, manually.

On April 11, 2024 soil penetration resistance (Eijkelkamp, The Netherlands; Cone Penetrologger, 1 cm^2, 60°, 5 penetrations per treatment) and track depth (vertical distance between the middle tire print and the horizontal rigid slat was measured with a ruler 6 times per treatment) were recorded as well as soil samples in ring cylinders (a´ 200 cm^3, 40 cm, in 10 cm layers, 5 reps.) for the determination of the bulk density were taken. The measured bulk density was used for calculating packing density, PD = bulk density (g cm^{-3}) + 0.005 × mass-%. clay + 0.001 × mass-%. silt) according to Renger et al. (2014).

Stem diameter, plant height, above-ground biomass (AGB), and grain yield were measured on September 5, 2024, by harvesting five maize plants per plot. Additional soil samples (20 cm × 20 cm × 28 cm) for earthworm investigation were taken with a spade from the treatment MP-CCno for un-wheeled, high and high-double on October 15, 2024. Samples were hand searched, earthworms were counted, biomass was taken, and adult earthworms were identified to species level.

The **long-term effect of soil compaction** was studied on an arable field (8 ha) in Raasdorf (Lower Austria, E: 16,598676; N: 48,238764). The calcaric Chernozem of alluvial origin with has an average pH-value of 7.7 and a soil texture of clayey sand (22% clay, 8% silt, 71% sand). The arable field has been under ploughless cultivation with a tine cultivator (25 cm) for more than ten years. Crops since 2016: yellow oat, winter wheat, spring durum wheat, winter wheat, winter durum wheat, winter barely, sugar-beet, spring durum wheat (2023). Plant residues were left on the field. After stubble-field skimming in July 2024, 6 pits (3 pits in-field (IF1, IF2, IF3 – non compacted) and 3 pits headland (HL1, HL2, HL3 - compacted) were dug with a digger to a depth of 1.2 m.

Sampling for total soil carbon (TC), total soil organic carbon (TOC) and total soil N (TN) were carried out in 6 layers (0-10, 10-20, 20-30, 30-40, 40-50, 50-70 and 70-100 cm). Three cylindrical rings (volume: 200 cm^3) per layer were taken for the determination of bulk density and saturated hydraulic conductivity (Ks). The soil samples were analyzed in the lab of the Federal Agency for Water Management, Institute for Land and Water Management Research in Petzenkirchen, Austria. The Ks was measured by applying the constant head method (Dane and Topp, 2002), the core samples were subsequently dried at 105°C to determine soil bulk density. Total C and N contents were measured by dry combustion (EN 15936:2022), inorganic C contents were measured by Scheibler method (EN ISO 10693:2014) and subtracted from total C to determine TOC.
All statistical analyses were performed using IBM® SPSS® Statistics 21 and RStudio. Kruskal–Wallis tests were used for analyzing the penetration data followed by Dunn's test with Bonferroni correction ($p < 0.05$). Harvest data in the short-term effect study and all parameters in the long-term effect study were tested using ANOVA and Student-Newman-Keuls test ($p < 0.05$).

RESULTS AND DISCUSSION

Short term effects:

Track depth was significantly influenced by all three factors: load, tillage, and cover crops. Among the load treatments, track depth increased in the order: Low < High < High-double. For tillage, the order was CT < NT < MP, with the mouldboard plough resulting in the deepest tracks (Figure 1).

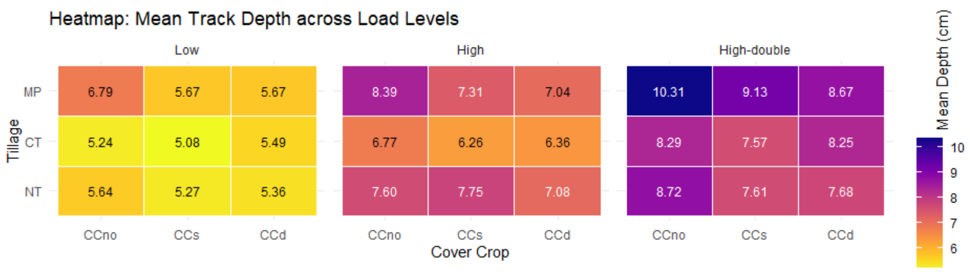

Figure 1: Mean tire track depth (cm) affected by tillage of cover crops (MP=Mouldboard Plough, CT=Cultivator, NT=No Till), cover crop mixture (CCno = No cover crop, CCs = shallow rooted cover crops, CCd = deep rooted cover crops) and wheel load (low, high, high-double), n=18, April 11th, 2024

Regarding cover crop treatments, track depth followed the pattern: CCd ≈ CCs < CCno, with the absence of cover crops leading to the greatest depth. As seen in Figure 1**,** the combination of CCs and CT resulted in the least track depth, indicating the most favorable condition for minimizing track depth. In contrast, the greatest track depth was observed under the combination of MP and CCno. The effect of cover crops on track depth was likely influenced by re-compaction of the soil through sowing.

Packing density (PD) was affected by the traffic load (Figure 2). Only NT and MP as well as high load and unwheeled treatments were included in this analysis. For cover crops, only CCno and CCd were sampled; however, as no significant effect of cover crop was observed, results are presented jointly. Across all depths, wheeled treatments showed higher packing density than unwheeled ones. MP showed the highest value under high load for the depth of 30-40 cm. Differences diminished with increasing depth.

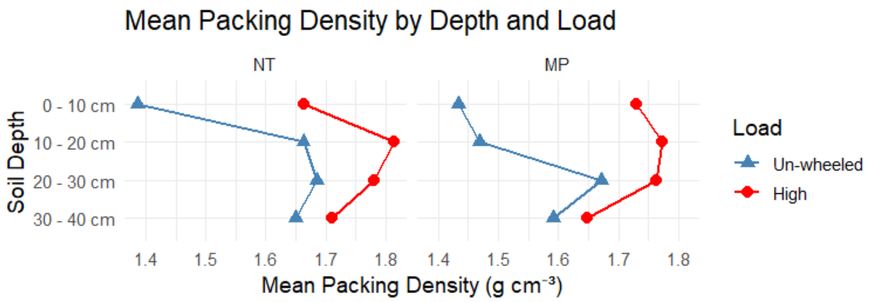

Figure 2: Mean packing density (g cm^{-3}) through tillage of cover crops (MP=Mouldboard Plough, NT=No Till) and loads high and un-wheeled (n=22) for different depths. Samples from April 2024.

Soil penetration resistance from April showed no significant effect of cover crop treatments according to the Kruskal-Wallis test. However, load had a significant effect on penetration resistance (Figure 3) and was therefore examined in more detail. Across all load levels, a distinct compaction peak was observed around 5 cm in depth, and a clear separation between load intensities was evident down to 40 cm. Like the packing density results, the effect of load decreased with increasing depth. When further broken down by tillage treatment, a trend emerged showing that CT resulted in the lowest penetration resistance across loads for lower depths. In unwheeled plots, the characteristic effect of mouldboard ploughing was clearly visible, with looser soil in the upper layer and increased resistance below the ploughing depth, reflecting the typical stratification induced by this tillage method.
The **earthworm analysis** (Table 1) showed a lower abundance and weight of earthworms in the double-wheeled treatment, which could be due to higher compaction. The effects in the high-single wheeled treatment were inconsistent especially with consideration of the two extreme values (275 and 325 adults m^{-2}; 105.0 g m^{-2} and 127.5 g m^{-2}) for the adults in the high load treatment and it is possible that the different soil moisture contents have also affected the earthworm abundance.

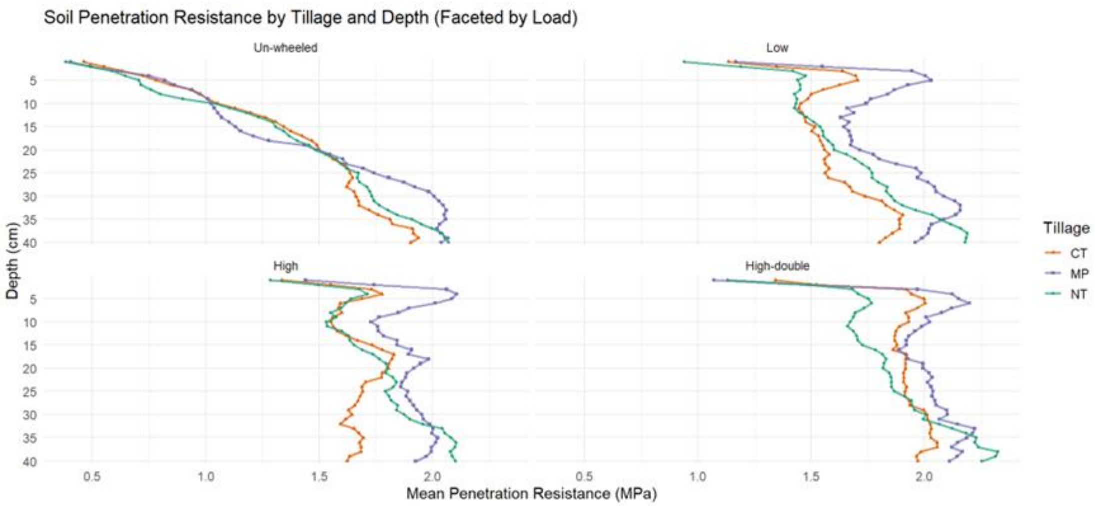

Figure 3. Overall soil penetration resistance in different load treatments, 45 penetrations per load and tillage. Sampling on April 11th, 2024. Soil moisture in un-wheeled soil: 0 – 10 cm: 24.9%, 10 – 20 cm: 29.4%, 20 – 30 cm: 28.2%.

Table 1. Abundance and biomass weight of juvenile and adult earthworms affected by the load. Sampling on October 15, 2024, on the plots with factor combination MP-CCno, 12 samples per treatment.

Load	Soil moisture (m/m %)	Juvenile (1 m^{-2})	Juvenile (g m^{-2})	Adult (1 m^{-2})	Adult (g m^{-2})	Total (1 m^{-2})	Total (g m^{-2})
Un-wheeled	21.1	275	23.6	75	25.6	375	49.2
High	19.5	375	29.7	100	33.8	475	63,5
High double	18.5	300	22.1	50	17.3	350	39.4

Selected harvest data are shown in table 2. While seed number was uniform across treatments (76,000 plants ha^{-1}), lower emergence was observed under the "High" and "High-double" wheel load treatments. This is likely due to compaction-related issues such as poor seed slot closure, reduced water contact, and potential bird damage.

Table 2: Selected harvest data 2024: basal stem diameter, plant height and dry crop yield (AGB= above-ground biomass, grain of maize yield biomass) affected by cover crop mixture (CCno = No cover crop, CCs=shallow rooted cover crops, CCd = deep rooted cover crop), tillage for cover crop (MP=Mouldboard Plough, CT=Cultivator, NT=No Till) and wheel load.

			Plant number seeded[1)]		**Plant number harvested [2)]**	
	Stem diameter (cm)	**Plant height (cm)**	**AGB yield (kg ha^{-1})**	**Grain of maize yield (kg ha^{-1})**	**AGB yield (kg ha^{-1})**	**Grain of maize yield (kg ha^{-1})**
Cover crop						
CCs	20.5	225[ab3)]	12,957	6,206[a]	9,615	4,599[a]
CCd	20.9	229[b]	14,444	6,995[b]	10,709	5,195[b]
CCno	20.4	221[a]	13,218	6,012[a]	10,150	4,500[a]
Tillage for CC						
MP	20.5	226	16,160[c]	7,804[c]	11,992[c]	5,542[b]
CT	20.5	222	11,348[a]	5,207[a]	8,627[a]	4,270[a]
NT	20.8	227	13,111[b]	6,201[b]	9,855[b]	4,597[a]
Load						
Un-wheeled	22.7[c]	249[d]	14,828[b]	7,041[b]	14,828[c]	7,041[c]
Low	21.3[b]	235[c]	14,690[b]	6,608[b]	14,690[c]	6,608[c]
High	21.9[b]	222[b]	14,763[b]	7,224[b]	7,900[b]	3,866[b]
High double	16.5[a]	196[a]	9,877[a]	4,468[a]	3,214[a]	1,544[a]

[1)] 76,000 plants/ha; [2)] mean plant number at harvest: 76,000 plants/ha for un-wheeled and low; 40,667 plants/ha for high and 24,733 plants/ha for high double; [3)] Statistically significant differences (p < 0.05 Student-Newman-Keuls) are with superscript letters between each factor.

For this reason, Table 2 includes two sets of yield values: one normalized to the full seeding rate to show potential yield, and another based on actual plant density at harvest. For harvested yields, Table 3 shows that the deep-rooted cover crop (CCd) resulted in the highest above-ground biomass (10,709 kg ha^{-1}) and grain yield (5,195 kg ha^{-1}), followed by the shallow-rooted mix (CCs) and the no-cover treatment (CCno). Tillage practices also had a notable effect: mouldboard ploughing (MP) led to the highest harvested yields (11,992 kg ha^{-1} AGB; 5,542 kg ha^{-1} grain), while the cultivator (CT) produced the lowest. Yield reduction was most pronounced under increasing wheel load. In particular, the “High-double” treatment showed severe losses (3,214 kg ha^{-1} AGB; 1,544 kg ha^{-1} grain). While trends for normalized yields (based on seeding rate) were similar, the harvested yields more clearly reveal the practical impact of compaction on crop performance. The “High-double” load not only reduced plant numbers but also led to small, underdeveloped plants — evident in both plant height and basal stem diameter.

Long term effects:

The saturated hydraulic conductivity Ks (Table 3) shows a high variation between the depths and the treatments. The topsoil layer 0-10 cm has the highest Ks which corresponds with the stubble field skimming (disc harrow) in July after harvesting summer durum wheat. In the subsoil layer 30-40 cm and 40-50 cm, the HL has significantly lower saturated hydraulic conductivity than in IF.
The measured bulk density values (data published in Moitzi et al., 2025) were below the criteria for healthy soil condition established at European Union level (European Commission – Proposal for a Soil Monitoring Law, 2023), which is for a sand clay soil 1.58 g cm^{-3}. Only in the subsoil 30-40 cm, the bulk density was significantly higher in HL (1.49 g cm^{-3}) than in IF, (1.39 g cm^{-3}). The soil penetration measurement in April 2023 shows a significant differentiation between HL and IF especially in the subsoil (data published in Moitzi et al., 2025).

Table 3: Saturated hydraulic conductivity Ks (mm h^{-1}) measured in each pit of the headland (HL) and in-field (IF).

Soil depth (cm)	HL1	HL2	HL3	**Mean HL**	IF1	IF2	IF3	**Mean IF**
0-10	198	479	93	**257**	739	179	139	**352**
10-20	13	153	105	**90**	279	48	162	**163**
20-30	12	66	53	**44**	41	16	169	**75**
30-40	7	21	25	**18^{a}**	155	85	37	**92^{b}**
40-50	57	48	54	**53^{a}**	182	86	47	**105^{b}**
50-70	45	57	160	**87**	87	83	82	**84**
70-100	28	38	94	**53**	26	80	58	**55**

Statistically significant differences ($p < 0.05$) are shown for the comparison Mean HL and Mean IF, Student-Newman-Keuls.

The total soil carbon stock (soil depth: 1-100 cm) is about and more than 500 t C ha^{-1} (Moitzi et al., 2025). Between 55% and 72% of the total soil carbon is contributed by the inorganic carbon source (carbonate) and 28% to 45% by the organic carbon source. The variation of the inorganic carbon stock is explained by thickness of the different alluvial sedimentations in the soil forming process.
In contrast, the long-term technically induced soil compaction in the HL results in a higher stock of organic carbon (Table 4) and stock of total nitrogen (data published in Moitzi et al., 2025) than in IF. The accumulation of organic carbon and nitrogen in the compacted headland is explained by a reduced decomposition of soil organic matter due to mitigated air permeability. On average, the organic carbon stock and nitrogen stock were 28% and 43% higher in HL than in IF, respectively.

Table 4: Stock of organic C (t ha^{-1}) measured of each pit in headland (HL) and in-field (IF).

Soil depth (cm)	HL1	HL2	HL3	**Mean HL**	IF1	IF2	IF3	**Mean IF**
0-10	35.7	35.4	32.9	**34.7^b**	30.4	27.7	28.1	**28.7^a**
10-20	32.9	30.1	30.0	**31.0^b**	29.5	23.9	27.4	**27.0^a**
20-30	31.8	27.7	30.0	**29.8^b**	26.6	17.5	26.7	**23.6^a**
30-40	28.1	26.5	27.4	**27.3^b**	24.8	11.6	24.8	**20.4^a**
40-50	25.3	27.0	27.2	**26.5^b**	19.3	7.7	26.6	**17.9^a**
50-70	41.7	38.6	52.6	**44.3^b**	18.2	26.9	34.7	**26.6^a**
70-100	35.7	21.8	35.7	**31.1**	23.1	24.4	45.8	**31.1**
Total	**231.3**	**207.2**	**235.8**	**224.8^b**	**171.9**	**139.7**	**214.2**	**175.3^a**

Statistically significant differences ($p < 0.05$) are shown for the comparison Mean HL and Mean IF, Student-Newman-Keuls.

CONCLUSION

This field trial on the short-term effects of soil compaction investigated the impacts of tillage, cover crops, and wheel load on soil physical parameters and crop performance of maize. Track depth and packing density increased with traffic intensity, particularly under mouldboard ploughing (MP) without cover crops. In contrast, conservation tillage (CT, NT) and shallow-rooted cover crops reduced surface compaction effectively. Penetration resistance confirmed deeper compaction under high loads, while CT maintained a more favorable soil structure. Crop yields were significantly affected by traffic load: “High-double” loads drastically reduced emergence and harvest performance. The highest yields were achieved with deep-rooted cover crops and MP, though at the cost of greater compaction. These findings suggest that reduced tillage combined with deep-rooted cover crops can help maintain soil structure, while traffic load management is critical for sustaining yields. Optimizing both soil conservation and productivity requires a balance between tillage intensity and load management.

Headlands of arable cropping fields are evident sites for long-term effects on soil compaction. The higher field traffic frequency with increased wheel load in the headland resulted in higher soil penetration resistance in the subsoil. Also, the other soil physical parameters (saturated hydraulic conductivity, bulk density, air permeability) responded in the compacted headland – especially in the subsoil. This site-specific result indicates that the compacted soil in the headland accumulated organic carbon and nitrogen in the soil. This could be explained by a reduced decomposition of soil organic matter due to mitigated air permeability.

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