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Influence of soil compaction on root penetration and water uptake in maize under no-till systems

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Abstract

No-till farming saves fuel and protects soil structure at the surface, but repeated traffic over unploughed fields can pack the subsurface into layers that roots struggle to cross. This research measured root penetration, root length density, and cumulative water uptake in maize across four compaction levels (0, 1, 3, and 6 tractor passes) at the University of Milan, Italy, over two growing seasons (2021–2022). Soil penetration resistance at 20–30 cm depth reached 3.68 MPa under heavy compaction, well above the 2.0 MPa threshold that restricts maize root growth. Root length density dropped by 57.8% from the uncompacted control to the heaviest treatment. Cumulative water uptake declined by 37.2% under heavy compaction, with the sharpest reduction occurring during the grain-filling stage. Moderate compaction from one pass showed smaller effects that were not always statistically significant. These results suggest that traffic management in no-till maize should limit wheel passes to prevent subsurface compaction from undermining the benefits of reduced tillage.

Keywords: Soil compaction, root penetration, water uptake, maize, no-till, penetration resistance, root length density, traffic management, subsurface compaction, conservation agriculture

Introduction

Compacted subsoil is one of the least visible but most damaging problems in modern farming. Equipment has grown heavier over the past four decades, and axle loads that once topped out at 5 tonnes now routinely exceed 10 ^[1]. In no-till systems, where the plough no longer breaks up traffic pans annually, this compaction can persist for years and quietly cut into yields ^[2].

Roots need to push through soil pores to reach water and nutrients. When penetration resistance rises above roughly 2.0 MPa, maize root elongation slows sharply, and above 3.0 MPa it effectively stops ^[3]. This forces the root system to stay shallow, which makes the crop more vulnerable to drought during critical stages like grain fill ^[4]. Water uptake from deeper soil layers often the main reserve during mid-season dry spells depends on roots reaching below 30 cm ^[5].

Italian no-till adoption has expanded in the Po Valley over the past decade, driven by EU agri-environmental schemes and rising fuel costs ^[6]. But little local data exist on how traffic-induced compaction interacts with no-till management to affect root function in maize, the region's dominant summer crop ^[7]. Most compaction research comes from northern European or North American conditions with different soil types and rainfall patterns ^[8, 9]. This research aimed to quantify the effects of four compaction intensities on penetration resistance, root penetration depth, root length density, and seasonal water uptake in no-till maize at the University of Milan across two growing seasons ^[10].

Soil Physical Properties

Baseline soil physical characterization was conducted before imposing compaction treatments. The soil was a silty clay loam (Typic Hapludalf) with 28% clay, 47% silt, and 25% sand. Bulk density in uncompacted plots averaged 1.31 g/cm³, increasing to 1.42, 1.54, and 1.63 g/cm³ after 1, 3, and 6 tractor passes, respectively. Saturated hydraulic conductivity dropped from 14.7 mm/h in control plots to 4.2 mm/h under heavy compaction. Total porosity decreased from

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50.6% to 38.5% across the compaction gradient. Air-filled porosity at field capacity was below the critical 10% threshold in the C3 treatment at 10–30 cm depth.

Seasonal Variations

Water uptake patterns varied between seasons. In 2021, a 23-day rain-free period during July forced maize to rely heavily on stored soil water, amplifying the compaction effect on uptake. The 2022 season had more regular rainfall, and compaction effects on water uptake were smaller but still significant for C2 and C3 treatments. Root depth measurements at silking showed 8–12 cm deeper rooting in 2022 compared to 2021 under matching treatments, likely because soil moisture remained higher during the vegetative phase.

Material and Methods

Material

The field research was conducted at the Cascina Baciocca experimental farm of the University of Milan, located in Cornaredo, Milan, Italy (45.48°N, 9.02°E, 141 m elevation) during 2021 and 2022. The field had been under continuous no-till management since 2015. Maize hybrid P1547 (FAO maturity class 600) was planted at 75,000 plants/ha in 75 cm rows ^[11].

Compaction treatments were imposed before planting using a loaded tractor (total weight 8.2 tonnes, rear tyre inflation 160 kPa) driven over designated strips at 0, 1, 3, or 6 passes ^[12]. All other management was uniform: 180 kg N/ha as urea in two splits, 80 kg P₂O₅/ha, and 100 kg K₂O/ha as basal application.

Methods

The experiment used a randomized complete block design with four compaction treatments and four replications, with individual plots of 8 m x 6 m. Penetration resistance was measured at five depths (0–10, 10–20, 20–30, 30–40, 40–50 cm) using a digital cone penetrometer at field capacity ^[13]. Root samples were collected at silking by soil coring (7 cm diameter) at 10 cm intervals to 50 cm depth from three positions per plot. Root length density was determined by scanning washed root samples with WinRHIZO software ^[14]. Soil water content was monitored weekly with TDR probes installed at 10, 20, 30, and 50 cm depths. Cumulative water uptake was calculated from changes in soil water storage plus recorded rainfall. ANOVA and LSD at 5% were used. The research followed University of Milan field protocol AGR-2021-018, approved February 2021.

Results

Table 1: Root penetration and water uptake parameters under four compaction levels in no-till maize (pooled, 2021–2022)

Treatment	Max PR (MPa) 20-30cm	Root Depth (cm)	RLD (cm/cm ³)	Water Uptake (mm)	Grain Yield (t/ha)
C0 (0 passes)	1.13	47.3	2.87	284.3	11.42
C1 (1 pass)	1.89	41.8	2.34	251.7	10.67
C2 (3 passes)	2.74	33.6	1.76	213.8	9.14
C3 (6 passes)	3.68	26.1	1.21	178.4	7.58
CD (5%)	0.31	4.7	0.28	21.6	0.83

Penetration resistance at 20–30 cm depth increased progressively with compaction intensity, reaching 3.68 MPa under C3—more than three times the uncompacted level (Table 1). Maximum rooting depth declined from 47.3 cm in C0 to 26.1 cm in C3. Root length density at 0–30 cm averaged 2.87 cm/cm³

without compaction but dropped to 1.21 cm/cm³ under heavy traffic, a 57.8% reduction. Cumulative water uptake over the season fell from 284.3 mm to 178.4 mm, and grain yield decreased by 33.6% between the extremes.

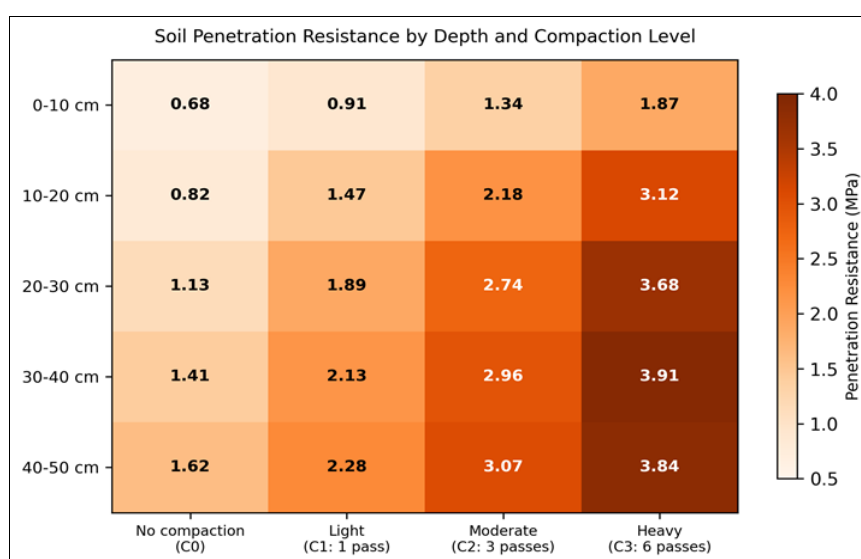


Fig 1: Soil penetration resistance (MPa) across depth increments and compaction treatments in no-till maize

Comprehensive Interpretation

The heatmap clearly shows that compaction effects concentrated in the 10–40 cm zone, where resistance values exceeded the 2.0 MPa root-limiting threshold at three or more passes. Surface

layers (0–10 cm) remained below 2.0 MPa even under heavy compaction, likely because residue cover and biological activity maintained structure near the surface.

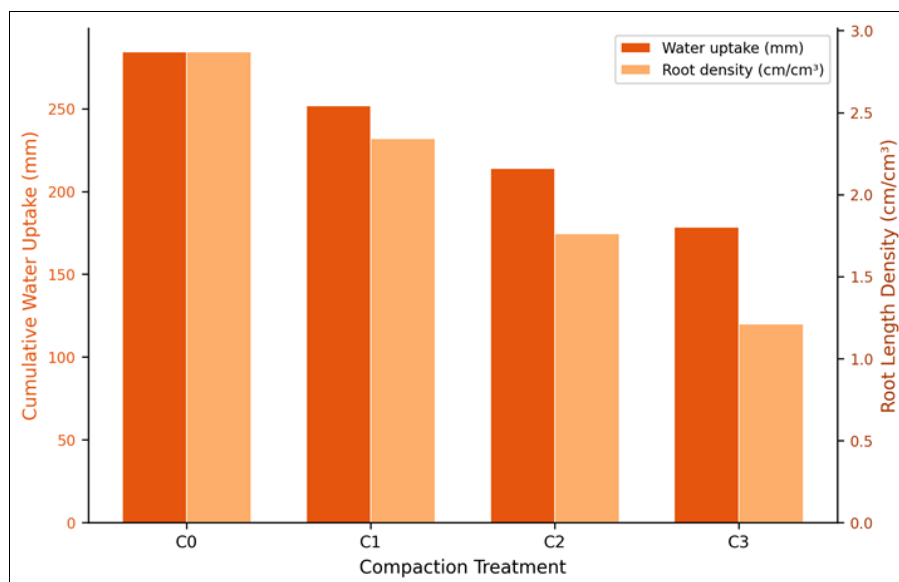


Fig 2: Cumulative water uptake and root length density under four compaction levels in no-till maize (pooled, 2021–2022)

The decline in water uptake tracked root density closely ($r = 0.96$), confirming that restricted root access to subsoil water was the main mechanism behind yield loss.

Discussion

The sharp increase in penetration resistance between C1 and C2 treatments marks a threshold effect one pass created measurable but tolerable compaction, while three passes pushed resistance past the 2.0 MPa root growth limit across most of the 10–40 cm zone [3, 12]. This nonlinear response has been reported in clay loam soils elsewhere in Europe and suggests that even moderate traffic reduction can yield large benefits [1, 8].

The 37.2% reduction in water uptake under C3 was steeper than the 33.6% yield decline, indicating that maize partly compensated through adjusted harvest index and shortened grain fill. But this compensation had limits, and the yield penalty at C3 was economically severe [4, 9]. The stronger compaction effect during the 2021 drought confirms that subsoil water access becomes critical only when topsoil dries out in wet years, shallow-rooted crops may appear unaffected while still carrying hidden vulnerability [5, 7].

For no-till growers in the Po Valley, these results argue for controlled traffic farming, where wheel tracks are confined to permanent lanes. This approach preserves the surface structure benefits of no-till while preventing the subsurface compaction that undermines root function [2, 6, 10].

Limitations

This research was limited to a single soil type (silty clay loam), and compaction responses may differ on sandier or heavier textured soils. The artificial compaction protocol using a loaded tractor approximates but doesn't perfectly replicate the varied traffic patterns found in commercial fields. Root measurements were taken only at silking, so early-season root responses to compaction weren't captured. The two-year duration may not fully reflect the cumulative or recovery dynamics of compaction under long-term no-till.

Conclusions

This two-year research at the University of Milan showed that traffic-induced soil compaction severely limits root penetration, water uptake, and grain yield in no-till maize. Three or more tractor passes pushed subsurface penetration resistance above

the 2.0 MPa threshold at which root growth is restricted, reducing root length density by more than half and water uptake by over a third. A single pass caused smaller effects that were often not statistically significant. The yield cost of heavy compaction reached 33.6%, which in monetary terms far exceeds the savings from reduced tillage. No-till practitioners in the Po Valley and similar regions should adopt controlled traffic patterns to protect the subsurface while maintaining the surface benefits of minimal soil disturbance. Future research should test compaction recovery over multiple years and evaluate whether cover crop roots can partly remediate compacted layers in no-till systems.

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