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Changes in Soil Hardness in Intensive Apple Orchards Influenced by Their Age

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ABSTRACT

Background: The research was carried out in 2024-2025 in intensive apple orchards on chernozem soils of the Tambov and Lipetsk regions of the Russian Federation. Soil compaction is a critical limiting factor in apple orchard productivity. As intensive orchards age, machinery traffic and root activity progressively alter soil physical properties. This study investigated the temporal and spatial dynamics of soil hardness (penetration resistance) across orchards of different ages and on three contrasting soil types in Central Russia.

Methods: Soil hardness was measured using a Wile Soil cone penetrometer at 10-cm depth intervals from 0 to 70 cm in row spacing aisles and trunk strips across orchards aged 1, 5, 12 and 50 years, established on podzolized chernozem, leached chernozem and meadow-chernozem soils. Three rootstocks M-9, 62-396 and 54-118 and corresponding planting densities were compared. Pearson correlation coefficients were used to quantify relationships between soil hardness and depth, orchard age and planting density.

Result: Soil hardness increased with depth on all soil types and at all orchard ages. The most rapid hardening was observed in the row spacing of 5-year-old orchards on podzolized chernozem. A plough sole with critical hardness 25.0-30,0 kg/cm^2 was recorded only in row spacing on podzolized chernozem at age 5. In trunk strips, soil hardness at age 12 was strongly influenced by rootstock and planting density: The M-9 rootstock at 4 × 0.75 m resulted in the lowest hardness up to 21.0 kg/cm^2 in the 0-60 cm layer, while rootstocks 62-396 and 54-118 at wider spacings showed critical hardness from 20-30 cm depth. By age 50, soil hardness decreased across all layers on all soil types. Inverse correlations between soil hardness and orchard age were significant in the 10-20 cm, r = -0.74; 40-50 cm, r = -0.94 and 50-60 cm, r = -0.91 layers.

Key words: Apple orchard, Chernozem, Orchard age, Penetration resistance, Plow sole, Rootstock, Soil compaction.

INTRODUCTION

Soil compaction is among the most widespread forms of soil degradation in agricultural systems, directly impairing root penetration, water infiltration and gas exchange (Passioura, 2002; Unnikrishnan *et al.*, 2023). Excessive soil hardness limits plant root elongation; both compacted and waterlogged conditions represent opposite ends of an optimal resistance range for root growth (Passioura, 2002). In apple orchards specifically, repeated passes of heavy machinery in row spacing generate compacted layers, while trunk strips-managed differently-may develop contrasting hardness profiles. It is especially important to know the hardness of different types of soil when growing peanuts, since the quality of its nuts is completely different when grown on soils of different granulometric composition (Hama-Ba *et al.*, 2022). The number of molehills in the entire soil profile depends on the hardness of the soil (Luna and Antinuchi, 2006). But there is also a feedback loop: if the tuco-tuco shrew (*Ctenomys minutus*) settles in the soil, then the hardness of the soil decreases under the influence of the vital activity of these animals (Galiano *et al.*, 2014). With an increase in soil moisture above 10%, the wear of implements decreases sharply (Mosleh *et al.*, 2013). When using No till technology (without tillage),the soil hardness is higher and the seeder coulters wear out more during sowing (Sarauskis *et al.*, 2013).

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The penetrometer (cone penetrometer) is a standard tool for quantifying soil resistance and diagnosing the presence and depth of the plough sole (Ebato, 2020). Critical penetration resistance for root growth is generally considered to be in the range of 25.0-30.0 kg/cm^2 (2.5-3.0 MPa) (Joshi, 2017). Soil hardness is closely related to moisture content: resistance increases as soil dries and simultaneous moisture measurement improves interpretive accuracy (Miyamoto *et al*., 2012; Puriyakorn *et al*., 1995). Soil organic matter additions and mulching reduce soil hardness by improving porosity and moisture stability (Khoirunnisak *et al*., 2024; Verma and Pradhan, 2024). Tillage depth directly determines the position of he plough sole, which typically forms at 15-20 cm depth (Jia *et al*., 2008).

Although soil compaction has been extensively studied in arable crop rotations, data from long-term intensive apple orchards are scarce. In orchards, the interplay between mechanical trafficking in aisles, root activity in trunk strips, orchard age, rootstock type and planting density creates a complex mosaic of hardness patterns that have not been adequately characterized. Understanding these dynamics is important for optimizing orchard floor management, selecting rootstocks for soil-sensitive sites and preventing irreversible soil degradation. Therefore, the objectives of this study were: (I) to determine how soil hardness varies with depth, production zone (row spacing vs. trunk strip) and orchard age across three soil types in intensive apple orchards of Central Russia; (II) to assess the influence of rootstock and planting density on soil hardness in the trunk strip zone and (III) to quantify correlations between soil hardness and depth, orchard age and planting density using layer-by-layer correlation analysis.

MATERIALS AND METHODS

The Study sites and soil types

The study was conducted in 2024-2025 at two locations in Central Russia. The first site was the Timiryazevsky Agricultural Processing Supply and Marketing Production Cooperative, Dolgorukovsky District, Lipetsk Region, where two orchards planted in 2020 (5 years old at the time of study) and 2013 (12 years old) were evaluated on leached chernozem and podzolized chernozem (heavy loamy granulometric composition). For comparative purposes, a 50-year-old extensive orchard planted in 1975 was also sampled at this site. The second site was the I.V. Michurin Federal Scientific Center, Michurinsky District, Tambov Region, where orchards on meadow-chernozem (thick, heavy loamy) were studied. All soils were classified by granulometric composition using the pyrophosphate method modified by S.I. Dolgov and A.I. Lichmanova (Revut, 1964).

Experimental design and orchard treatments

Observations were made in row spacing (aisles) and trunk strips for each combination of orchard age, soil type and rootstock. At the Timiryazevsky site, trees were planted at a spacing of 4.5 × 1.0 m on rootstock 62-396, with aisles managed under bare soil (black steam) and no drip irrigation. At the Michurin Federal Scientific Center, three rootstock/ spacing combinations were studied in the same orchard block, with aisles under cultivated grass cover (white clover and red fescue) and trunk strips managed as bare soil with drip irrigation. The experimental layout was fourfold repetition with systematic and consistent plot placement. The treatment combinations are summarized in Table 1. Trunk strips at all Michurin site treatments were managed as bare soil (black steam) with a drip irrigation system.

Soil hardness measurement

Soil hardness (penetration resistance, kg/cm^2) was determined in mid-September of each study year using a cone penetrometer (Wile Soil density meter) at a standardized soil moisture content of 60% of the lowest moisture capacity (field capacity). Measurements were taken at successive depth intervals of 10 cm from 0 to 70 cm, in both the row spacing zone and the trunk strip zone. At each measurement point, five replicate penetrometer readings were taken and averaged. The critical threshold for root growth impairment was defined as 25,0-30,0 kg/cm^2, consistent with published literature (Joshi, 2017; Passioura, 2002).

Statistical analysis

Pearson correlation coefficients (r) were calculated to quantify (I) the relationship between soil hardness and depth at each orchard age and production zone, (II) the relationship between soil hardness and orchard age in each 10-cm depth layer and (III) the relationship between tree planting density and soil hardness by layer. All calculations were performed in Microsoft Excel. Differences in soil hardness between production zones (row spacing and trunk strip) and among rootstock treatments were assessed graphically and by the magnitude of correlation coefficients.

RESULTS AND DISCUSSION

Soil hardness in relation to depth and orchard age on podzolized chernozem

On podzolized chernozem, soil hardness increased with depth at all orchard ages (Fig 1). Before orchard establishment, soil hardness in the 0-20 cm layer was below the critical threshold (25.0 kg/cm^2), with higher hardness commencing from 20 cm depth despite prior deep ploughing; the correlation between hardness and

Table 1: Experimental orchard treatments studied at I.V. michurin federal scientific center.

Rootstock	Apple variety	Planting scheme (m)	Feeding area per tree (m²)	Aisle management
M-9	Ligol / Lobo	4.0 × 0.75	3.0	Grass cover + drip irrigation
62-396	Ligol / Lobo	4.5 × 1.2	5.4	Grass cover + drip irrigation
54-118	Ligol / Lobo	4.5 × 2.0	9.0	Grass cover + drip irrigation

depth was r = 0.85-0.88. By age 5, hardness in the 0-20 cm layer had increased 1.5- 2.0-fold compared to pre-planting values, while hardness below 20 cm remained at an already critical level (~35 kg/cm^2); the depth-hardness correlation at this age was r = 0.71-0.90. By age 50 (extensive orchard), soil hardness decreased in all layers to a depth of 70 cm and was no longer critical for root growth; at this age, the depth-hardness correlation was r = 0.86-0.98.

Spatial differentiation between production zones was evident on podzolized chernozem at age 5 (Fig 2). In row spacing, critical hardness was observed from 30 cm depth, whereas in trunk strips it began from 40 cm depth. The largest differences occurred in the 20-30 cm layer, where row spacing hardness was approximately twice that in trunk strips. The depth-hardness correlation in row spacing was r = 0.71-0.74 and in trunk strips r = 0.83-0.90.

Soil hardness on leached chernozem

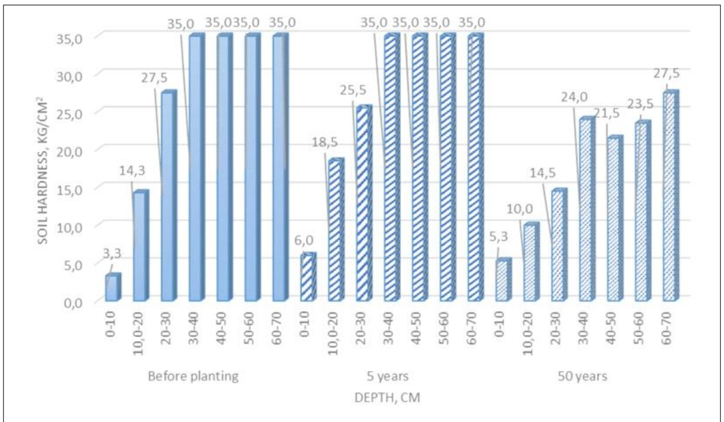
On leached chernozem, pre-planting soil hardness was low in the 0-40 cm layer and reached critical values only below 40 cm, with maximum hardness at 50-70 cm depth (Fig 3). The pre-planting depth-hardness correlation was r = 0.98. By orchard age 5, hardness decreased in all layers compared to pre-planting values, with the critical threshold reached only at 60-70 cm (26.5 kg/cm^2). In a 50-year-old extensive orchard on this soil, hardness was similar to that in the 5-year intensive orchard.

In the 5-year orchard, row spacing hardness in the 10-40 cm layer was higher than in trunk strips; in other layers, hardness was similar between zones (Fig 4). The depth-hardness correlation was r = 0.94-0.90 in row spacing and r = 0.98 in trunk strips.

Soil hardness on meadow-chernozem at orchard ages 5 and 12 years

On meadow-chernozem, the two production zones showed similar hardness profiles in a 5-year-old orchard, with small differences only at 40-50 cm depth (Fig 5). Critical hardness was reached from 30 cm in row spacing and from 40 cm in trunk strips. The depth-hardness correlation was r = 0.92-0.96 in row spacing and r = 0.94-0.95 in trunk strips.

By age 12, differences between zones became more pronounced: Row spacing hardness was higher than trunk



Error bars represent standard error of five replicate measurements.

Fig 1: Hardness of podzolized chernozem depending on the age of the apple orchard, kg cm^{-2} (*Timiryazev sky* cooperative).

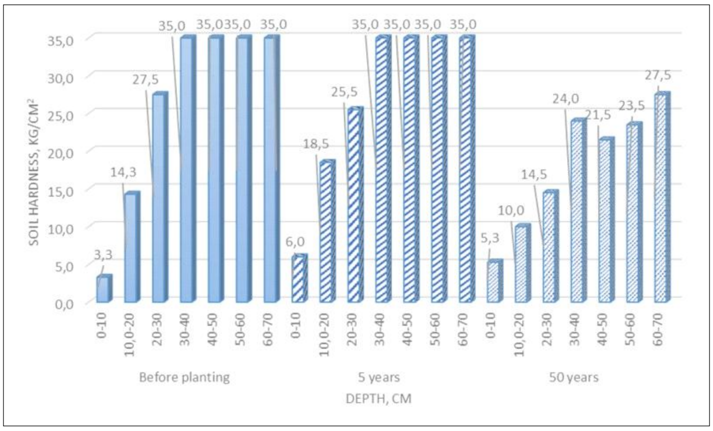


Fig 2: Hardness of podzolized chernozem depending on the production zone in a 5-year-old apple orchard, kg cm^{-2} (*Timiryazev sky* cooperative).

strip hardness in the 0-20 cm layer, while differences at greater depths were less consistent (Fig 6). In both zones, critical hardness was reached from 30 cm depth. The depth-hardness correlation at age 12 was r = 0.60-0.89 in row spacing and r = 0.90-0.93 in trunk strips.

Effect of rootstock and planting density on soil hardness in trunk strips at orchard age 12.

At age 12, soil hardness in trunk strips differed significantly among rootstock treatments (Fig 7). The M-9 rootstock (4.0 × 0.75 m; feeding area 3.0 m^2) maintained the lowest hardness throughout the profile: Up to 21,0 kg/cm^2 in the 0-60 cm layer, with hardness increasing slowly with depth (r = 0,60-0,80). In contrast, rootstocks 62-396 (4.5 × 1.2 m) and 54-118 (4.5 × 2.0 m) showed critical hardness from 20-30 cm depth, reaching 28.5-50,0 kg/cm^2 in the 20-60 cm layer; depth-hardness correlations were r = 0.90-0.93 for rootstock 62-396 and r = 0.79-0.91 for rootstock 54-118.

Layer-by-layer correlation analysis between planting density (trees ha^{-1}) and soil hardness revealed no significant relationship in the 0-10 cm layer (r = 0.11) or in the 50-60 cm layer (r = 0.43), but a strong positive correlation in the 10-50 cm zone: r = 0.80 at 10-20 cm, r = 0.92 at 20-30 cm, r = 0.68 at 30-40 cm and r = 0.82 at 40-50 cm. Thus, higher planting density (more roots per unit soil volume) was associated with lower soil hardness in the rhizosphere.

Comparison among soil types and effect of orchard age

In 5-year-old intensive orchards, leached chernozem had the lowest hardness across all layers (not exceeding 26.0 kg/cm^2 on average in the 0-70 cm layer), followed by meadow-chernozem (critical hardness at 40-70 cm: 33.5-35.0 kg/cm^2) and podzolized chernozem (critical hardness from 20-70 cm: 30.5-35.0 kg/cm^2) (Fig 8).

Layer-by-layer correlation analysis between orchard age and soil hardness showed contrasting patterns by depth. In the 0-10 cm layer, no significant age-hardness relationship was found (r = -0.26), nor in the 20-30 cm layer (r = -0.15) or the 60-70 cm layer (r = -0.17). The absence of an age effect at 0-10 cm is attributed to continuous mechanical loosening of this layer during inter-row cultivation. The lack of correlation at 20-30 cm reflects the persistent plough sole formed by repeated tillage at constant depth.

Inverse relationships were significant in the 10-20 cm layer (r = -0.74), 30-40 cm layer (r = -0.48), 40-50 cm layer

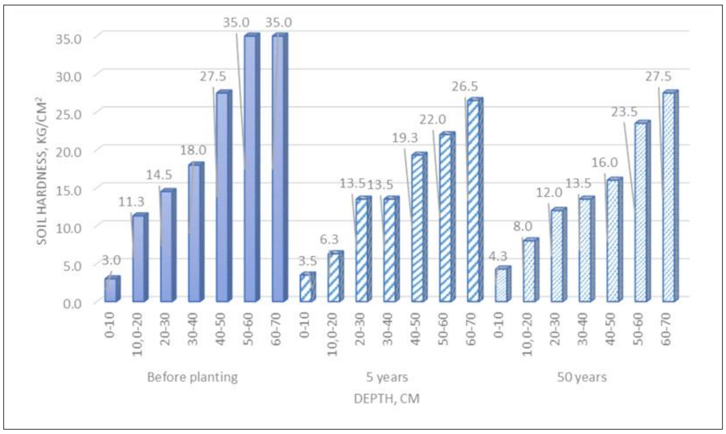


Fig 3: Hardness of leached chernozem depending on the age of the apple orchard, kg cm^{-2} (*Timiryazev sky* cooperative).

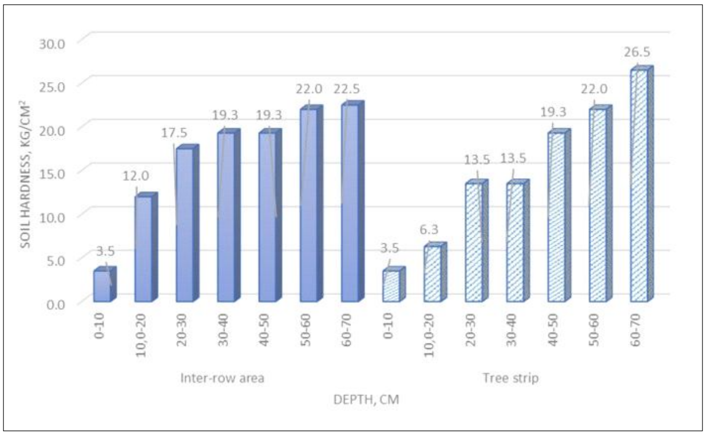


Fig 4: Hardness of leached chernozem depending on the production zone in a 5-year-old apple orchard, kg cm^{-2} (*Timiryazev sky* cooperative).

(r = -0.94) and 50-60 cm layer (r = -0.91), indicating a general decrease in soil hardness with increasing orchard age in the 10-60 cm zone.

Soil hardness and depth

The consistent increase in soil hardness with depth observed across all soil types, orchard ages and production zones is attributable to the combined effect of gravitational consolidation, diminishing organic matter with depth and reduced biological activity in deeper layers (Passioura, 2002).

The strong correlations between depth and hardness (r > 0.85 in most cases) confirm penetration resistance as a reliable indicator of soil structural differentiation in orchard systems. The relatively weaker depth-hardness correlation in row spacing of 5-year orchards (r = 0.71-0.74) compared to trunk strips (r = 0.83-0.90) is consistent with the irregular compaction pattern generated by machinery traffic, which creates high surface-layer hardness and a pronounced plough sole (Ebato, 2020; Jia *et al*., 2008), disrupting the otherwise, monotonic increase of hardness with depth.

Row spacing and trunk strips

The higher soil hardness in row spacing compared to trunk strips is a well- recognised consequence of repeated machinery passes in intensive orchards. The 2-fold difference in hardness at 20-30 cm depth on podzolized chernozem at orchard age 5 (Fig 2) is consistent with published data on traffic-induced compaction in fruit orchards and confirms that even young orchards develop significant compaction gradients within five years of establishment. Trunk strip management (bare soil, no traffic) clearly mitigates hardening, particularly in the upper 40 cm. These findings underscore the importance of minimising wheel loads and traffic frequency in row spacing and suggest that conservation of the trunk strip as a traffic-free zone is a key management strategy for preserving soil physical quality.

Soil type differences

Leached chernozem showed the lowest overall hardness and the most favourable structural stability, consistent with its higher organic matter content and more stable

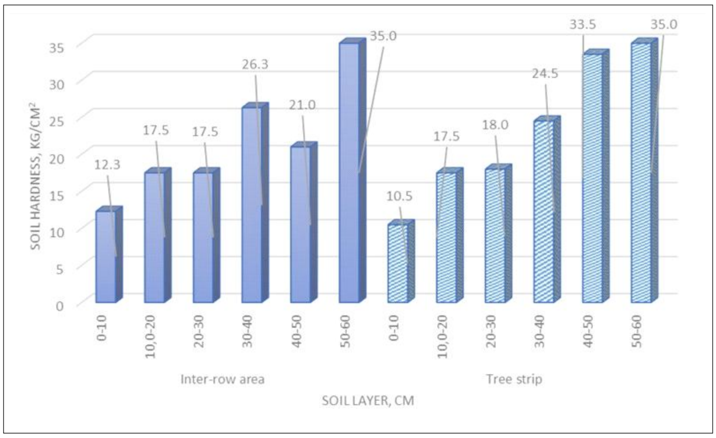


Fig 5: Hardness of meadow-chernozem soil in an intensive 5-year-old apple orchard on rootstock 62-396, kg cm^{-2} (I.V. Michurin Federal Research Center).

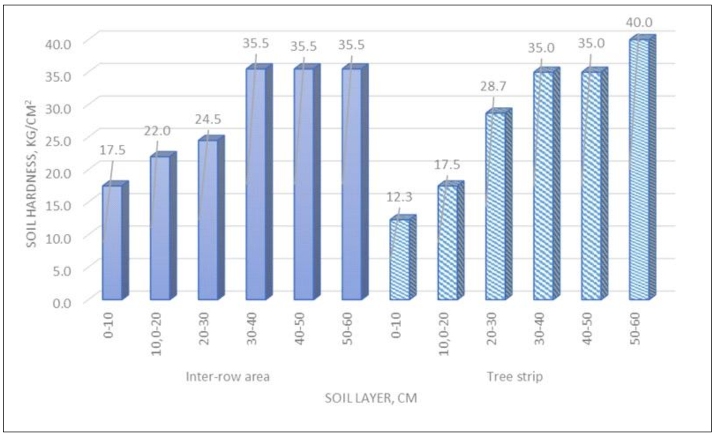


Fig 6: Hardness of meadow-chernozem soil in an intensive 12-year-old apple orchard on rootstock 62-396, kg cm^{-2} (I.V. Michurin Federal Research Center).

aggregate structure relative to podzolized and meadow-chernozem soils. The critical hardness threshold on leached chernozem was reached only at 60-70 cm depth in young orchards, indicating that this soil type is most resilient to compaction under intensive management. By contrast, podzolized chernozem already showed critical hardness below 20 cm depth prior to orchard establishment, suggesting that pre-existing subsoil compaction is a major constraint on this soil type irrespective of orchard age. These results highlight the need for soil-type-specific management strategies: On podzolized chernozem, deep subsoiling prior to planting may be warranted.

Effect of rootstock and planting density

The significantly lower soil hardness in the rhizosphere of M-9 rootstock trees (feeding area 3.0 m^2) compared to 62-396 and 54-118 rootstocks (feeding area 5.4 and 9.0 m^2, respectively) at age 12 is explained by the greater root density per unit soil volume at higher planting densities. Denser root networks physically loosen soil, increase porosity through root channel formation and contribute more organic carbon from root turnover (Abolla *et al*., 2019; Khoirunnisak *et al*., 2024). The strong positive correlation between planting density and reduced hardness in the 10*50 cm zone (r = 0.68-0.92) provides quantitative support for the hypothesis that dense root systems progressively ameliorate subsoil compaction. This finding has practical implications for rootstock selection in soils prone to compaction: High-density plantings on dwarfing rootstocks may, over time, favour better soil structural conditions in the rhizosphere than sparse plantings on vigorous rootstocks.

Effect of orchard age

The inverse relationship between orchard age and soil hardness in the 10-60 cm zone (r = -0.74 to -0.94 in critical layers) is an important finding with management implications. It suggests that, despite continued machinery traffic, the ameliorative effect of root activity, organic matter accumulation and biological soil loosening outweighs compactive forces in the medium and long term. This is consistent with the observations in the 50-year-old

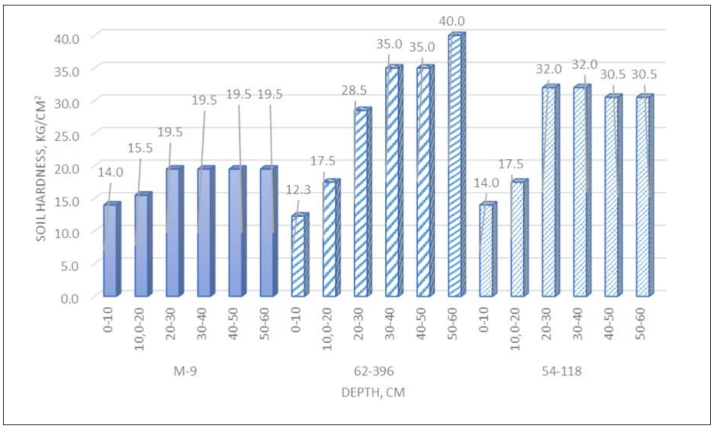
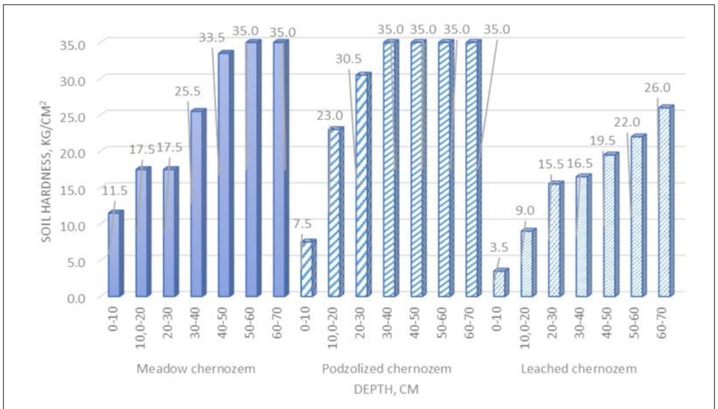


Fig 7: Hardness of meadow-chernozem soil in trunk strips of intensive 12-year-old apple orchards depending on the rootstock, kg cm^{-2} (I.V. Michurin Federal Research Center).



Bars represent mean values across both production zones and measurement replicates.

Fig 8: Comparison of soil hardness among three soil types in 5-year-old intensive apple orchards, kg cm^{-2}.

extensive orchard, where hardness was below the critical threshold throughout the profile. The absence of an age effect at 0-10 cm (due to tillage) and at 20-30 cm (due to the plough sole) indicates that these layers are primarily determined by management, not biological processes, and must be addressed through direct intervention. A practical implication is that transitioning to minimum-tillage or no-till management in row spacing may allow the natural age-related amelioration process to eventually extend into the plough sole zone.

CONCLUSION

In the aisles of intensive apple orchards in Central Russia, at orchard ages of 5-12 years, the hardness of chernozem soils at a depth of 30 cm can reach or exceed the critical threshold 25,0-30,0 kg/cm^2, with values up to 50,0 kg/cm^2 recorded in some cases. However, with the further growth of trees, soil hardness in the apple tree rhizosphere 10-60 cm layer decreases to approximately 20 kg/cm^2 due to an increase in root density. Leached chernozem has lower hardness than podzolized chernozem and meadow-chernozem soils.

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Disclaimers

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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