00 — INTRODUCTION

FEDERAL & STATE AGENCY RESEARCH COMPILATION

Soil Compaction & the Failure of Revegetation.

A consolidated review of bulk density thresholds, persistence timelines, and remediation effectiveness — drawn from FHWA, USDA Forest Service, NRCS, NPS, and state DOT research published between 1978 and 2024.

PRIMARY SOURCES	STUDIES SYNTHESIZED	RESEARCH SPAN
5 Agencies	*120+*	*1978 – 2024*

01 — WHAT COMPACTION ACTUALLY DOES

SOIL PHYSICS & ROOT BIOLOGY

When pores collapse, *roots stop.*

A well-structured soil is roughly half mineral aggregate, with the remaining volume divided about evenly between water and air-filled pores. Compaction breaks the connectivity between macropores, reducing total pore volume and severing the gas-exchange network roots depend on.

When compacted, three failures occur simultaneously and reinforce one another:

- **Mechanical impedance.** Root tip elongation is severely reduced as soon as roots encounter compacted layers.
- **Restricted gas exchange.** Recent plant-biology research shows roots actively sense compaction via the gaseous hormone ethylene. In compacted soil, ethylene cannot diffuse away through the broken pore network — it accumulates around the root and chemically halts further root growth.
- **Reduced water availability.** Pore collapse cuts both water-holding capacity and infiltration. Water that does fall is shed as runoff rather than absorbed.

Aboveground consequences follow inevitably: reduced leaf area, lower total photosynthesis, and elevated mortality of newly planted vegetation.

Sources: Pandey et al. (2024) *Uncovering root compaction response mechanisms,* Plant Cell & Environment; Kozlowski (1999) *Soil compaction and growth of woody plants;* Bacq-Labreuil et al. (2022) *Limited resilience of the soil microbiome to mechanical compaction,* Communications Biology.

02 — WHEN ROOTS STOP GROWING

USDA-NRCS · SCHUELER CENTER FOR WATERSHED PROTECTION

Bulk density *thresholds*.

Bulk density is the dry weight of soil divided by its volume — including pores. The denser the soil, the less air, water, and root space available. NRCS publishes texture-specific thresholds for when root growth begins to suffer and when it stops entirely.

SOIL TEXTURE	IDEAL BD	AFFECTS GROWTH	RESTRICTS ROOTS
Sands & loamy sands	< 1.60	≥ 1.69	> 1.80 g/cm³
Sandy loams & loams	< 1.40	≥ 1.63	> 1.80 g/cm³
Sandy clay loams, clay loams	< 1.40	≥ 1.60	> 1.75 g/cm³
Silts & silt loams	< 1.30	≥ 1.60	> 1.75 g/cm³
Silt loams, silty clay loams	< 1.40	≥ 1.55	> 1.65 g/cm³
Sandy clays, silty clays (35–45%)	< 1.10	≥ 1.49	> 1.58 g/cm³
Clays (> 45%)	< 1.10	≥ 1.39	> 1.47 g/cm³

Field measurement. NRCS and Minnesota Stormwater Manual treat **300 psi** on a cone penetrometer as the threshold for root-restrictive resistance. When more than 50% of readings exceed 300 psi, compaction is considered *moderate;* when more than 75% exceed it, *severe.*

Sources: USDA-NRCS, *Soil Quality Indicators — Bulk Density* (Arshad, Lowery & Grossman 1996); Schueler, T. (2000) *The Compaction of Urban Soils,* Center for Watershed Protection Technical Note #107; Minnesota Pollution Control Agency, *Stormwater Manual — Soil Compaction Indicator Sheet.*

03 — CONSTRUCTION-INDUCED COMPACTION

LICHTER & LINDSEY · RANDRUP · FRIEDMAN · SMITH

Construction *creates* the problem.

Highway construction, mass grading, and equipment traffic each produce documented, additive increases in soil bulk density. Even sites where contractors employed selective grading and protected planting areas showed compaction from incidental traffic.

MASS GRADING	CONSTRUCTION TRAFFIC	COMPACTION DEPTH
+0.34	+0.17	12–22"
to +0.35 g/cm³ bulk density increase from construction with mass grading (Randrup 1998; Lichter & Lindsey 1994).	to +0.40 g/cm³ from equipment traffic alone — independent of grading (Lichter & Lindsey 1994; Smith 1999; Friedman 1998).	below the soil surface — where heavy-equipment compaction layers typically form, beyond reach of conventional cultivators.

A 2016 study of Ontario roadside tree-planting sites measured surface bulk densities of **1.45 to 1.49 g/cm³** at 0–10 cm and **1.55 to 1.67 g/cm³** at 20–30 cm — already above the ideal threshold for any soil texture and approaching the root-restriction line for clay loams. Schueler reports rights-of-way and building pads at 95% compaction reach **1.6 to 2.1 g/cm³,** approaching concrete (2.2 g/cm³).

Sources: Vidrih et al. (2016) *Organic amendments decrease bulk density and improve tree establishment in roadside plantings,* Urban Forestry & Urban Greening; Schueler (2000) Technical Note #107; Randrup & Lichter (2001) *Measuring soil compaction on construction sites.*

04 — HOW LONG IT LASTS

PICCHIO ET AL. (2020) · 121-STUDY SKID TRAIL REVIEW

Decades, *not* seasons.

PERSISTENCE RANGE	YIELD LOSS, YEAR 1–2	AIR PERMEABILITY
2–5 dec	−90%	−94%
Compaction impacts persisted at least two to five decades after logging operations across all studied biomes (Picchio et al. 2020 review of 121 studies).	Crop yield reduction in the first two seasons following a single mechanical compaction event (Bacq-Labreuil et al. 2022).	drop after compaction; gas diffusion fell 59%. Neither property fully recovered within four growing seasons (same study).

> *Without deep tillage, decades may pass before deep compaction recovers its original bulk density — and tillage alone will not restore the soil's hydrologic function.*
>
> — FHWA, ROADSIDE REVEGETATION MANUAL, §10.1.2

Natural recovery processes — freeze–thaw cycles, animal burrowing, root growth — operate primarily within the upper 12 to 24 inches of soil. Construction-induced compaction routinely extends below this zone, where natural recovery is essentially absent on human timescales. Once compaction becomes severe enough that plants and soil microbes cannot establish, the natural recovery feedback loop collapses entirely.

Sources: Picchio, R. et al. (2020) *Natural recovery of skid trails: a review,* Canadian Journal of Forest Research; Bacq-Labreuil, A. et al. (2022) *Limited resilience of the soil microbiome to mechanical compaction,* Communications Biology; FHWA *Roadside Revegetation: An Integrated Approach,* Chapter 10.

05 — MECHANICAL REMEDIATION

ANDRUS & FROEHLICH 1983 · USFS TECH REPORT 0834-2828-MTDC

Equipment matters. *A lot.*

Not all "ripping" is equal. Operational testing on USFS lands found dramatic performance differences between standard rock rippers, brush rakes, and properly-configured winged subsoilers. Equipment choice alone can change the outcome from minimal to near-complete compaction shatter.

WINGED SUBSOILER	ROCK RIPPER	BRUSH RAKE
80%+	18–43%	38%
of compacted soil shattered between tines (Andrus & Froehlich 1983 operational tests, USFS).	shatter — leaves intact compacted soil between tine paths.	shatter — comparable to the lower range of single-tine rippers.

Operating principles documented across FHWA, USFS (Kees 2008), and Minnesota Stormwater Manual:

— **Reach the layer.** Shanks must run 1 to 2 inches below the compacted zone — typically 12 to 22 inches deep for highway-construction sites.

— **Respect critical depth.** Below a soil-specific critical depth, tines cause *more* compaction rather than fracturing. Wetter and more plastic soils have shallower critical depths.

— **Surface scarification is not subsoiling.** Shallow loosening helps germination only. Once roots reach the hard layer below, growth halts and the project fails.

— **Soil moisture window matters.** Soil must be between field capacity and wilt point; outside that window, tines slice or block-lift rather than shatter.

Sources: Andrus, C. & Froehlich, H. (1983) *An Evaluation of Four Implements Used to Till Compacted Forest Soils*, Oregon State University; Kees, G. (2008) *Using*

06 — TILLAGE ALONE IS NOT ENOUGH

OLSON 2010 · OLSON ET AL. 2013 · PATTERSON & BATES · KOLSTI ET AL.

The compost *multiplier.*

A growing body of comparative research shows that mechanical decompaction alone produces marginal recovery — often statistically indistinguishable from untreated controls. Organic-matter incorporation is the multiplier that makes subsoiling pay off.

BULK DENSITY DROP

18–37%

reduction in bulk density on compost-amended plots versus controls (Olson 2010 — residential study).

HYDRAULIC CONDUCTIVITY

2.7–6.1×

increase in saturated Ksat on compost-amended plots compared to control plots.

TILLAGE ALONE, KSAT

0.5–2.3×

control — meaning tillage without amendment produced no consistent improvement (Olson et al. 2013).

A separate Minnesota Pollution Control Agency synthesis quantified average bulk-density change by remediation type:

REMEDIATION METHOD	BULK DENSITY DECREASE	SOURCE
Tilling alone	0.00 to 0.02 g/cm³	Randrup 1998 · Patterson & Bates 1994
Specialized soil loosening	0.05 to 0.15 g/cm³	Rolf 1998
Soil amendments (other)	0.17 g/cm³	Patterson & Bates 1994
Compost amendments	0.25 to 0.35 g/cm³	Kolsti et al. 1995
Reforestation (long-term)	0.25 to 0.35 g/cm³	CWP Article 36

07 — CITATIONS

PRIMARY REFERENCES

Sources & *citations.*

01 FHWA — Roadside Revegetation: An Integrated Approach to Establishing Native Plants and Pollinator Habitat

Chapter 10.1, Soil and Site Treatments — covers tillage equipment, subsoiler configuration, organic amendments, and topographic enhancement. Anchor reference for federal-aid road projects.

environment.fhwa.dot.gov / env_topics / ecosystems / roadside_revegetation

02 Kees, G. (2008) — *Using Subsoiling To Reduce Soil Compaction,* Tech Report 0834-2828-MTDC

USDA Forest Service, Missoula Technology & Development Center. Definitive USFS field guide to subsoiler configuration, shank design, critical depth, and operating procedure.

fs.usda.gov / t-d / pubs / pdfpubs / pdf08342828

03 USDA-NRCS — *Soil Quality Indicators: Bulk Density* (Arshad, Lowery & Grossman 1996)

Source of texture-specific root-restriction thresholds, ideal bulk-density values, and field penetrometer interpretation.

nrcs.usda.gov / soil-quality-indicators

04 Schueler, T. (2000) — *The Compaction of Urban Soils,* Watershed Protection Techniques 3(2): 661–665

Center for Watershed Protection Technical Note #107. Source of bulk-density values for undisturbed and urban soils, and construction-activity bulk-density increases.

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05 Picchio, R. et al. (2020) — *Natural recovery of skid trails: a review,* Canadian Journal of Forest Research

Quantitative review of 121 studies. Documented persistence of compaction impacts at 2–5 decades across temperate, tropical, and boreal forest biomes.

cdnsciencepub.com / doi / 10.1139 / cjfr-2020-0419

06 Bacq-Labreuil, A. et al. (2022) — *Limited resilience of the soil microbiome to mechanical compaction within four growing seasons,* Communications Biology

Documents −90% yield loss in seasons 1–2, −94% air permeability, −59% gas diffusion. Properties did not fully recover after 4 seasons.

ncbi.nlm.nih.gov / pmc / articles / PMC9723577

07 Olson, N. et al. (2013) — *Compost amendment of compacted urban soils,* Journal of Environmental Quality

Source of the Ksat 2.7–5.7× control finding for compost plots, and the 0.5–2.3× control finding for tillage-only plots.

ncbi.nlm.nih.gov / pubmed / 23353881