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Review Article

Occasional Tillage in Long-term No-till Systems: A Conditional, Diagnose-first Framework

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ABSTRACT

No-till (NT) is widely promoted because it protects the soil surface, reduces erosion, and can improve soil health over time. However, in some long-term NT fields, problems may gradually build up such as, traffic-related compaction, hard layers that restrict roots, strong nutrient and pH stratification near the surface, difficult seeding in heavy residues, and weed shifts that become harder to manage. These constraints have revived debate on whether occasional tillage (OT; also termed strategic or rotational tillage) is necessary within NT systems. Based on recent global synthesis evidence and mechanistic understanding from soil physics, we argue for a conditional position: OT is not universally necessary, but can be a justified risk-management intervention when (i) a clear, yield-limiting constraint is present, (ii) NT-compatible options are unlikely to resolve the constraint within an acceptable timeframe, and (iii) OT can be done with minimum risk to soil cover and erosion control. Global synthesis evidence suggests a modest average yield increase under OT relative to continuous NT (+3.2%; 95% CI 2.0-4.5%), with stronger responses for deep loosening/subsoiling, wheat systems, and cooler/wetter climates. At the same time, it can reduce surface soil organic carbon (- 4.1%) alongside improved porosity (+12.5%) and reduced bulk density (-5.5%). This matters for soil physics because it is mainly about soil structure - how pores, soil strength, infiltration, and root growth change under long-term NT, and how quickly they recover after one-time tillage. The same synthesis identifies a timing window (~5-6 years after NT adoption) when a one-time OT event may be most effective, coinciding with the onset of compaction in many systems. We present a practical guide that starts with proper diagnosis, then tries no-till options. If tillage is still needed, it should be the least disturbing option and followed by residue cover, traffic control, cover crops, and monitoring. Used this way, occasional tillage can act as a repair tool, not routine tillage.

Key words: Soil compaction, Soil structure, Soil organic carbon, Decision framework

Why this matters

Adoption of no-till (NT) has expanded globally as part of conservation agriculture (CA), driven by its clear benefits for erosion control, surface soil protection, and, in many environments, improved water conservation and operational efficiency (Hobbs *et al*., 2008; Derpsch *et al*., 2010). From a soil physics perspective, NT systems typically gain from reduced surface disturbance, stabilization of aggregates near the soil surface, and the development of biopores and continuous macropore networks that support

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infiltration and root exploration. However, long-term NT is not a single management practice but a system that depends on tractor and implement passes, residue and crop-rotation management, nutrient placement strategies, and weed and pest management. Where these complementary components are weak or where soils and climates create binding constraints, negative impacts may accumulate over several years (Dang *et al*., 2015; Blanco-Canqui and Wortmann, 2020). Commonly reported challenges include machinery traffic (repeated wheel and axis loads) induced compaction layers, strong nutrient and pH stratification in the upper soil layers, residue-related seeding problems, and weed communities (including herbicide-resistant populations) that become increasingly difficult to control.

These realities have stimulated renewed interest in occasional tillage (OT; also strategic, rotational, or periodic tillage) defined here as an infrequent tillage operation introduced into an otherwise continuous NT system (Dang *et al*., 2018). The controversy is not whether tillage can fix some constraints (it often can), but whether the fix is necessary, how often it should occur, and whether the short-term gains justify potential losses of NT-derived ecosystem services. We suggest occasional tillage only if it is truly needed, based on field diagnosis, and with safeguards so no-till benefits are not lost (Dang *et al*., 2015; Blanco-Canqui and Wortmann, 2020).

What we mean by 'occasional tillage'?

We refer to OT as a one-time or infrequent mechanical soil disturbance (e.g., deep loosening or subsoiling, strip tillage, shallow non-inversion mixing, or inversion tillage) applied after several years of NT, followed by a return to NT as the normal practice. Occasional tillage should be distinguished from reduced tillage (practiced every season or year), or repeated tillage to deal with repeated problems without changing the system, or emergency tillage carried out under high erosion risk or wet conditions (Dang *et al*., 2015; Peixoto *et al*., 2020; Blanco-Canqui and Wortmann, 2020).

From a soil physics standpoint, the most applicable OT interventions are those that (a) directly address a diagnosed physical constraint (e.g., a root-limiting dense layer), (b) minimize disruption of surface cover and protect organic matter, and (c) are coupled with management that prevents re-compaction or re-stratification.

Problems that can build up under long-term no-till

Compaction and hard layers

Even when tillage is avoided, soil can compact due to wheel loads, repeated traffic on wet soil, and lack of control in machinery movements. NT may reduce near-surface bulk density in some systems over time, but can also promote a persistent dense layer below the depth disturbed by seeding operations (Mondal *et al*., 2020). Compaction constrains root elongation, reduces infiltration and aeration, and increases runoff and ponding (Mondal and Chakraborty, 2023).

Stratification of nutrients, pH and organic matter

With repeated surface fertilizer applications and limited mixing, NT commonly produces strong vertical gradients in available P and K and in pH, particularly in the top 0-5 cm layer (Crozier *et al*., 1999; Zhao *et al*., 2015). Long-term no-till often leads to strong stratification of soil organic carbon, with higher concentrations in surface layers and reduced levels at depth (Franzluebbers, 2002). Stratification can be beneficial under some conditions (e.g., surface-rooting crops), but can limit deeper root activity and nutrient access.

Residue and planting constraints and biotic pressure

Residue retention is crucial to CA, but in high-biomass systems, its overload can hamper planting, delay soil drying or warming, increase pests, and favour certain residue-borne diseases (Soane *et al*., 2012). These problems can be effectively dealt with better residue distribution and seeding technology, but not always.

Weed community shifts and herbicide resistance

NT often relies more heavily on herbicides and cover-crop suppression of weeds (Friedrich, 2005).

Over time, this can select for problematic weed communities and herbicide resistance. OT may be proposed as one tool to reset seedbank vertical distribution or disrupt perennial weeds, but it can also stimulate germination and increase erosion risk if misused (Oreja *et al*., 2025).

What the evidence says

Evidence from long-term no-till (NT) systems consistently supports this message (Table 1). Occasional (or strategic) tillage is not a universal need, but it can be useful as a targeted option when specific constraints build up and do not respond to 'NT-first' fixes (e.g., cover crops, rotations, residue and nutrient management, controlled wheel tracks, or drainage corrections). Many long-term studies report that a single or infrequent tillage usually causes minimal or short-lived negative effects on soil physical, chemical, and biological indicators, and soil structure and SOC often regain within 1-2 years, especially when the system returns quickly to NT (Çelik *et al*., 2019; Brevilieri *et al*., 2024). At the same time, repeated or aggressive tillage can reverse NT benefits, so frequency and intent matter (Díaz-Zorita *et al*., 2004).

A recent global meta-analysis provides strong quantitative evidence (Yan *et al*., 2026). It synthesized 94 articles with 1079 paired comparisons and 356 yield comparisons, and found that OT increased crop yield by an average of 3.2% (95% CI 2.0-4.5) compared with continuous NT, but responses were clearly heterogeneous and depended on operation type, crop, climate, and soil. In the same synthesis, subsoiling (>30 cm) gave larger yield gains (+7.1%) than ploughing or rotary tillage, which showed smaller or often non-significant effects. Wheat showed stronger positive response (+6.3%) than other crops, and benefits were more frequent in cooler climates (mean annual temperature 8-16°C; +6.8%) and in wetter environments (mean annual precipitation >1200 mm; +3.6%). Some soil groups (e.g., Phaeozems) showed particularly large yield responses, indicating that soil structure, organic matter status, and rooting conditions strongly influence outcomes. Importantly, the same meta-analysis also noted that OT intensity (how often OT was done) was not a consistent driver of yield response; this supports the idea that OT should be need-based rather than scheduled (Yan *et al*., 2026).

Another global meta-analysis focusing on soil physical properties also supports 'conditional OT'. (Peixoto *et al*., 2020). It reported that OT can reduce compaction and improve soil physical condition, but the direction and persistence depend on the implement and on whether NT is already consolidated. For example, effects were strongest with deeper or more structural operations (e.g., subsoiling), and benefits could persist beyond a year in some situations, while more aggressive surface disturbance tended to reduce aggregate stability. This synthesis also reported that OT did not always raise yields, but yield gains were more likely under specific 'stress' contexts (for example, where water restriction and low water retention limit productivity).

Taken together, these two meta-analyses suggest that OT can be considered, but only in the right problem-place-time combination (Çelik *et al*., 2019; Blanco-Canqui and Wortmann, 2020). A key practical insight is the 'timing window' for OT. The mean time since NT adoption when OT was applied was about 6.4 years, and the estimated timing for the most positive yield response was about 5.7 years (95% CI 5.7-10.7) (Peixoto *et al*., 2020). However, this should not be read as 'till every 6 years'. It is better understood as OT is more likely to help when it is introduced near the onset of a diagnosed constraint (often compaction and restricted rooting), rather than after decades of unresolved problems. That reading fits well with long-term field evidence showing that a carefully chosen one-time tillage, followed by return to NT, often has little lasting negative effect on soil indicators and crop growth over several years (Kirkegaard *et al*., 2020).

The soil-property trade-offs are real and must be stated plainly. In the global synthesis that quantified soil changes, OT improved physical condition by increasing porosity (+12.5%) and reducing bulk density (-5.5%), consistent with relief of root-limiting compaction (Stavi *et al*., 2011; Peixoto *et al*., 2020). At the same time, OT reduced soil organic carbon (SOC) (-4.1%), and total nitrogen also tended to decline. It may be also noted that SOC, total N, available P and K often decreased in the upper

Table 1. Evidence synthesis (global meta-analysis + supporting literature) of occasional tillage (OT) effects relative to continuous no-till (NT)

Outcome (OT vs continuous NT)	Direction and magnitude	Key moderators (where OT has maximum impact)	Why it happens (likely)	What to be careful about
Crop yield (overall)	+3.2% (2.0-4.5) across 356 yield comparisons (94 studies, 1079 paired comparisons)	Subsoiling (>30 cm): +7.1%; wheat: +6.3%; maize: +4.4%; biannual cropping: +5.5%; MAT[1] 8-16°C: +6.8%; MAP[2] >1200 mm: +3.6%	Yield gains are most consistent when OT relieves compaction (root-limiting) or improves seedbed function; benefits are context-dependent	High heterogeneity; effects depend on OT type, timing, residue/traffic/fertility context
Timing of first OT after adopting NT	Critical timing threshold at 5.7 years (5.7-10.7) of continuous NT	Most effective early (<6 years), coinciding with onset of compaction	Early intervention may prevent persistence of compact layers	Threshold is not universal
Soil bulk density	Decreased (-5.5%)	Greater improvements with subsoiling; coarse textures often respond better than clays	Mechanical loosening increases macroporosity and reduces resistance to root penetration	Effects can be transient; risk of re-compaction if soil is tilled wet
Soil porosity	Increased (+12.5%)	Deep loosening; contexts with compaction; residue return may enhance response	Creates transient pore space and reconnects pore networks; may improve infiltration and aeration	Porosity gains may not persist unless stable structure is rebuilt
Soil organic carbon (SOC) stock/SOC concentration	Reduced (-4.1%); depth redistribution reported	Losses more likely with inversion and repeated disturbance; redistribution rather than uniform loss	Mixing redistributes surface SOC through the tilled layer and can accelerate mineralization; SOC moves deeper but recalcitrant pools may be exposed	Trade-offs depend on tillage intensity and post-OT residue cover; important to assess by depth and equivalent soil mass
Total nitrogen	Trivial or variable at whole-profile; depth redistribution reported (decrease in upper and increase in lower layers)	Linked with SOC redistribution and residue/fertility management	Mixing redistributes organic N; short-term mineralization may occur	Net TN change may be non-significant; must interpret with depth-resolved sampling
Available P and K	Improved in surface layer; redistribution reported	NT system with strong stratification; interaction with fertilization/placement	Mixing reduces extreme surface stratification and can alter rooting access patterns	Benefits depend on baseline stratification and placement strategy after OT
Soil water content / Hydraulic functions	Improves when OT alleviates compaction; significance varies by study and metric	Compacted soils; coarse textures; deep loosening; residue retention/cover crops post-OT	Improved pore continuity and reduced runoff and ponding when dense layer is relieved	Short-term gains may be offset if surface cover is reduced or soil structure collapses after rainfall

[1]Mean Annual Temperature; [2]Mean Annual Precipitation

layers (0-10 or 0-20 cm) but increased in the next deeper layers (10-20 or 20-40 cm), suggesting redistribution rather than a uniform loss across the profile (Peixoto *et al*., 2020). This is why soil physics and soil fertility assessments after OT should use depth-resolved sampling (and ideally equivalent soil mass approaches) rather than relying on only a shallow surface layer.

Evidence beyond yield and soil physics also matters for farm decisions. OT can help manage herbicide-resistant weeds and, sometimes, soil-borne pests by disturbing the seedbank or disrupting biological cycles, but it can also shift weed communities if used without an integrated weed strategy (Oreja *et al*., 2025; Peixoto *et al*., 2020).

Environmental outcomes are context-specific. Some studies show OT can reduce dissolved P losses or help address stratification, yet poorly timed OT can increase erosion risk and greenhouse gas emissions, especially on vulnerable soils or slopes (Peixoto *et al*., 2020; Uusitalo *et al*., 2024; Melland *et al*., 2017). Economic evidence suggests OT often does not change profitability much compared with continuous NT when it is used sparingly and for clear agronomic benefits, but routine OT without fixing the underlying cause can become an added cost with little benefit (Dang *et al*., 2015; Vandeveer *et al*., 2023).

Overall, the evidence supports a conditional position. Occasional tillage is not a routine part of long-term no-till, but it can be justified in specific situations. It should be adopted only when a real, yield-limiting problem is clearly diagnosed in the field, such as a root-restricting compact layer, severe waterlogging from poor infiltration, or an unmanageable weed situation, and when the best no-till options are unlikely to fix the problem within a reasonable time. Even then, the goal is not to 'go back to tillage', but to use the least-disturbing operation that can solve the constraint, at the right soil moisture, and with strong safeguards. Because tillage can also reduce surface soil carbon and disturb soil biology, it should be treated as a carefully planned step, followed by monitoring to confirm both benefits and any costs.

Figure 1 provides a practical decision framework intended for researchers, advisers, and producers. It guides users through: (i) identifying symptoms and

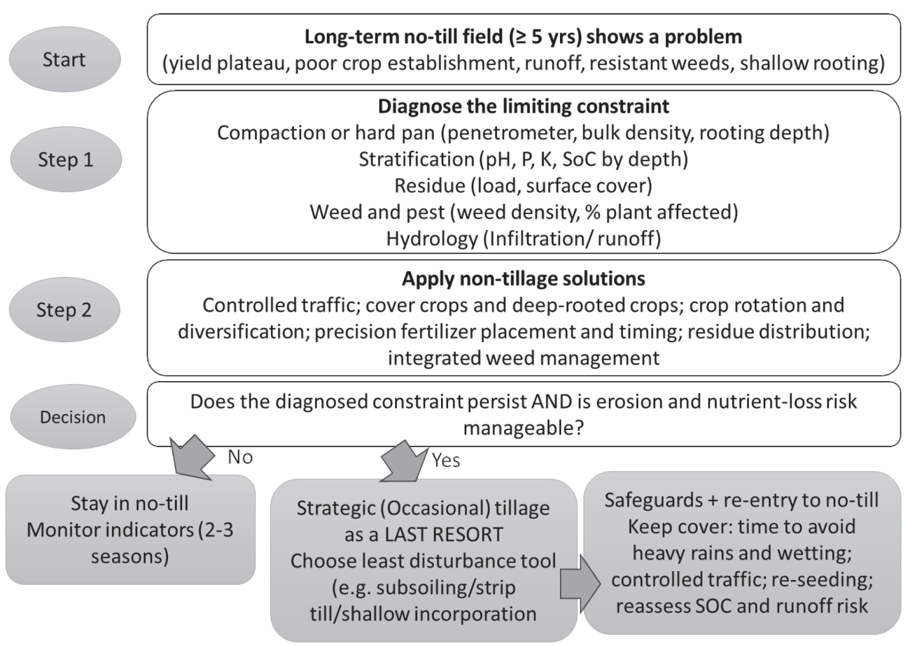

Fig. 1. A decision framework for occasional or strategic tillage in long-term no-till systems [The framework first tries no-till solutions, checks key risks (erosion risk, soil wetness, and machinery wheel loads), and uses occasional tillage only as a last step, choosing the simplest option and following it with a recovery plan and monitoring]

confirming diagnoses; (ii) prioritizing NT-compatible remedies; (iii) evaluating erosion/climate risk windows; (iv) selecting the least-disturbing OT option only when justified; and (v) monitoring recovery and re-establishing NT system integrity (Table 2).

How to do it with the least harm?

Choose the minimum effective disturbance

Deep loosening/subsoiling targeted to the constraint layer and limited to traffic lanes or strips often has a more defensible physics rationale than full-width inversion, because it can reduce penetration resistance while preserving surface cover. Inversion should be reserved for specific, well-justified cases (e.g., severe weed seedbank reset or amendment incorporation).

Operate only under suitable soil water conditions

Soil strength and structure response to disturbance are strongly controlled by water content. Tilling wet soil increases smearing, destroys aggregates, and accelerates re-compaction. A practical rule is to operate when the soil is dry enough to fracture rather than smear (verified by field tests), and to avoid repeated passes.

Keep the soil covered and manage erosion risk

Because erosion risk is highest immediately after disturbance, OT should be scheduled in low-risk windows and paired with residue retention, cover crops, and rapid re-coverage of bare soil. Where erosivity is high or slopes are vulnerable, OT is rarely defensible.

Prevent re-compaction (traffic control)

The most common failure mode of OT is that the field returns to the same compaction state within 1–3 seasons due to traffic. Controlled traffic farming, load management, and post-OT cover crops with deep rooting are essential to translate a mechanical 'reset' into a longer-term structural trajectory.

Monitor and learn: OT should be treated as an experiment

OT should not be an unmeasured intervention. Minimum monitoring should include crop yield, soil penetration resistance/bulk density, infiltration (or a proxy such as runoff/ponding), and depth-resolved SOC and nutrient stratification.

What to monitor: Indicators and practical thresholds

Monitoring should match the problem we are trying to fix, and it should be simple enough that farmers and researchers can repeat it over seasons (Table 2). If compaction is the issue, soil strength (e.g., penetration resistance at a comparable soil moisture), bulk density, and root depth or rooting pattern should be measured, and a basic infiltration test done (single-ring or even a timed water-entry test) plus field observations of ponding and runoff. If stratification is the concern, layered soil sampling (0-5, 5-10, 10-20 cm, and where relevant, 20-40 cm) should be done for pH, available P and K, and exchangeable acidity (link this to crop tissue tests if possible). If weed infestation is faced, weed species shifts, patch maps, and resistance are to be recorded. Because occasional tillage can change carbon and nutrients with depth, depth-wise SOC (ideally using an equivalent soil mass approach) sampling and monitoring of residue cover after the operation is recommended. Finally, crop yield and water productivity must be monitored for at least 3 to 5 seasons to judge whether benefits persist or fade.

Conclusion

Future work should move beyond the simple question of 'does occasional tillage help', and instead identify when, why, and for how long it helps, and what are the true trade-offs. First, studies need clearer and comparable definitions of the intervention - tillage type, depth, intensity, width (field vs strips), timing, and frequency, along with the soil moisture condition at operation and the machinery regime before and after. Second, outcomes must be measured in ways that match soil physical processes, especially depth-wise assessments of compaction layers, pore continuity, infiltration and preferential flow, and root distribution, rather than only shallow sampling (say 0-10 cm). Third, carbon and nutrient effects should be reported by depth and, where possible, by equivalent soil mass so that redistribution is not assumed as net loss or gain. Fourth, persistence matters. Many benefits of loosening hard pan may

Table 2. Decision guide for using occasional tillage in long-term no-till systems

Symptom (typical in long-term NT)	Field diagnostics	'NT-first' options	When OT may be useful	Lowest-disturbance OT option	Safeguards and recovery plan
Traffic-induced compaction / dense soil layer; restricted rooting; ponding and/or runoff; yield stagnation	High penetration resistance at near-field capacity; BD above critical; poor infiltration; stunted roots at a certain depth; wheel-track yield maps	Controlled traffic; avoid field operations when wet; rotation; deep-rooted cover crops; residue retention with improved seeding equipment; organic inputs; gypsum where appropriate	Constraint persists despite NT-first remedies; compaction coincides with repeated yield penalty or persistent waterlogging; compaction located below typical seeding depth	Targeted loosening or subsoiling in wheel tracks; strip-tillage; shallow non-inversion loosening if problem is near-surface	Operation in dry soil; keeping e"30% cover; minimizing wheel passes; returning to NT immediately; monitoring BD or infiltration or yield for at least 2–3 years
Nutrient and pH stratification (P, K, acidity/alkalinity) limiting rooting and nutrient uptake	Layered soil tests (0-5, 5-10, 10-20 cm) show steep gradients; roots concentrated near surface; nutrient deficiency symptoms despite adequate application; subsoil acidity or Al toxicity	Banding or deep placement; variable-rate placement; repeated surface liming (fine lime); lime/gypsum placement via coulters/injection; organic amendments on surface with proper placement	Very high stratification with yield loss; need to incorporate soil amendments (e.g., lime) into a specific layer to correct pH	Very shallow incorporation (vertical till) if issue is at 0-10 cm; one-time inversion or mixing where incorporation is essential (site-specific)	Low-erosion window for OT; residue retention; avoiding multiple passes and re-establish surface cover rapidly; resuming NT with placement-based nutrient strategy
Herbicide-resistant weeds or hard-to -control perennials; weed community shift; rising control costs	Testing herbicide resistance or observing crop failure; seedbank indicators; patch mapping; perennial rhizome spread	Diversified rotations; cover-crop mulches; competitive cultivars; diversified herbicide modes; harvest weed-seed control; targeted grazing where feasible	System viability threatened (resistance crisis) and IWM fails; need to reset seedbank placement or disrupt perennials	Targeted inversion or shallow cultivation in problem patches; one-time strategic inversion and follow-up with cover crop and rotation	OT as one tool within IWM; planning post-tillage residue cover; avoiding repeated OT; monitoring weed shifts for 3-5 years
Residue overload and planting difficulties; slow warming or drying; crop establishment failure; pest emergence	Emergence or crop stand counts; residue mass; seed placement issues (hairpinning); soil temperature and moisture near seeding; pest scouting	Upgrading of planter (row cleaners, closing wheels); residue distribution at harvest; strip-till in-row warming; variety and date adjustments	Repeated crop stands failures despite equipment and management fixes; residue-borne issues cannot be managed via rotation or surface handling	Shallow residue mixing or vertical till; strip tillage limited to seeding zone; to avoid full-width inversion unless essential	Maintaining cover between rows; avoiding erosion-prone periods; return to NT; monitor erosion, soil cover, and crop emergence
Residue-associated diseases and pests in narrow rotations; unacceptable risk to yield or grain quality	Pest and disease diagnostics; association with residue and rotation history; spatial patterns	Diversification; resistant varieties; chopping and spreading of residue; biological control; altered planting dates	Recurring outbreaks with limited rotation options; clear linkage to residue load; economic thresholds exceeded	Targeted shallow incorporation where inoculum reduction is expected; to avoid unnecessary mixing	One-off bridge to improved rotation; re-establish soil cover; return to NT with improved residue and crop health plan
Surface sealing, poor infiltration; localized salinity or sodicity management needs	Infiltration test; crust strength; dispersion indicators; salinity mapping; runoff observations	Organic inputs; cover crops; gypsum or other ameliorants applied with proper placement tools; improved drainage/traffic control	Surface constraint persists and blocks emergence; need to incorporate ameliorant into surface layer	Very shallow mixing with minimal inversion; localized intervention only	Avoiding soil exposure (bare soil); maintaining mulch; resuming NT; monitoring infiltration and crusting, EC or ESP where relevant

disappear if re-compaction occurs, so trials should run for at least 3 to 5 years after the operation and movement of farm machinery must be controlled. Fifth, we need better links between soil structure recovery and biological rebuilding of the soil, including the role of cover crops, rooting traits, residue management, and earthworms or biopores. Finally, decision rules must be tested on-farm using simple diagnostics and thresholds, so that the 'strategic tillage' becomes a measured, last-resort tool rather than a mere justification for returning to routine tillage.

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