



Soil-plant-water relationships and crop yield under conservation agricultural practices: A biophysical basis for tailored adoption

Mosisa Tujuba Wakjira¹, Renske Hijbeek¹, Joost van Heerwaarden¹, John Koestel², Sara Bonetti³, Johan Six⁴, Katrien Descheemaeker¹

¹Plant Production Systems Group, Wageningen University and Research, 6708PB, Wageningen, The Netherlands

²Soil Quality and Soil Use, Agroscope, 8046 Zurich, Switzerland

³Laboratory of Catchment Hydrology and Geomorphology, EPFL, 1951 Sion, Switzerland

⁴Institute of Agricultural Sciences, ETH Zurich, 8092 Zurich, Switzerland

10 *Correspondence to:* Mosisa Tujuba Wakjira (mosisa.wakjira@wur.nl or mosisatujuba@gmail.com)

Abstract. Conservation agriculture is widely promoted to reduce soil degradation, restore and maintain soil health, enhance crop productivity, and mitigate greenhouse gas emissions. This generally entails three core practices: reduced soil disturbance, permanent organic soil cover, and crop rotation. However, the universal applicability of these practices across diverse biophysical and socioeconomic contexts is under debate due to inconsistent agronomic performance and practical challenges associated with implementing all three practices simultaneously. To better understand the associated biophysical dynamic, we evaluated changes in soil-plant-water relationships and crop yields under five practices: no-till without residue (NT), reduced tillage without residue (RT), no-till with residue (NT+RR), reduced tillage with residue (RT+RR) and conventional tillage with residue retention (CT+RR), each compared with conventional tillage without residue retention (CT), using a global meta-analysis of observations from 338 studies across 361 experimental sites. Overall, yield declined by 6.1% ($p = 0.024$) under NT. However, yield reductions diminished with increasing tillage intensity (from NT to CT) and residue retention ($p = 0.041$). Sensitivity analysis revealed that yield reductions under NT are likely driven by compaction-driven adverse changes in soil hydraulic and mechanical properties limiting water movement (infiltration, redistribution and drainage), retention, and availability to crops, and root growth. Specifically, NT, irrespective of residue management, reduced soil near-saturated hydraulic conductivity – a property governing soil water replenishment, redistribution and drainage -- by 26.9% ($p = 0.008$), increased soil penetration resistance by 29.4% ($p < 0.001$), and changed the pore size distribution resulting in smaller air-capacities and larger wilting points. When reduced tillage and residue retention treatments were combined (RT+RR), yield variability was more strongly associated with changes in soil organic carbon and saturated hydraulic conductivity than water retention, and penetration resistance. Yield responses varied with local climate and soil type. NT increased yields in semi-dry climates (aridity index: 0.3-0.65) by 16.3% ($p = 0.004$). In contrast, NT reduced yield in humid regions (-7.2%, $p < 0.001$) as well as in dry regions (-8.3%, $p = 0.038$) where irrigated agriculture is likely to dominate. These yield responses by climate context closely mirrored the observed differences in saturated hydraulic conductivity. Yield penalties were generally greatest in clayey soils (e.g., under RT -19.3%, $p = 0.047$) and consistently diminished toward sandy soils, both under NT and RT.



These findings highlight the need for context-specific implementation of conservation agriculture to achieve balanced agronomic and environmental benefits.

35

1. Introduction

Conservation agriculture (CA) is promoted as one of the sustainable agricultural production pathways to reduce soil degradation, restore and maintain soil health, enhance climate resilience, and mitigate greenhouse gas emissions (FAO, 2022). It is centred on a suite of soil and crop management practices founded on three pillars: minimal soil disturbance (adopting no-till or reduced tillage), permanent soil organic cover (via residue retention or organic mulching), and crop rotation (FAO, 2022; Kassam et al., 2009; Pretty and Bharucha, 2014). The theoretical justification for CA practices is that, when adopted as a ‘package’, these practices collectively create a root environment that is physically and chemically conducive, and biologically active, thereby supporting sustainable intensification of crop production while providing multiple agroecosystem services (Kassam et al., 2009; Lal, 2015). In other words, the combined adoption of these practices is expected to create conducive agronomic conditions (Hobbs et al., 2008).

Reduced soil disturbance is thought to support soil structural stability and pore connectivity, which are vital for maintaining optimal soil-plant-water relationships, governing soil water movement, soil water storage, soil aeration, root growth, and plant water and nutrient uptake (Rabot et al., 2018). It also favours soil and water protection by reducing soil erosion and agrochemical fluxes (Jarvis, 2007), soil biodiversity protection by allowing uninterrupted life cycles and biological activities of earthworms and microbes (Hartmann and Six, 2023), and climate change mitigation through enhanced carbon sequestration (Six et al., 2002). Permanent organic soil cover contributes to soil and water protection from erosion and to agrochemical pollution control by reducing surface runoff and supports soil biodiversity by supplying food and substrate for soil biota. It also contributes to climate change mitigation through enhanced soil carbon storage by promoting soil organic matter (SOM) return and indirectly supporting plant CO₂ uptake (Hartmann and Six, 2023; Lal, 2015). Additional benefits of residue retention include weed suppression, alleviation of soil compaction, and regulation of soil temperature. Crop rotation, in turn, introduces alternating rooting patterns that improve soil-plant-water relationships; enhances soil microbial diversity which plays a key role in disrupting pest, disease, and weed cycles; and facilitates nitrogen fixation, especially when legumes are integrated, thereby increasing in-situ nutrient availability (Giller, 2001; Hobbs et al., 2008; Zhao et al., 2022).

60

In practice, however, most farmers implement CA only partially rather than as a package (Araya et al., 2024; Giller et al., 2009; Heller et al., 2024; Wade et al., 2015). As a result, the anticipated agronomic CA benefits are often not fully achieved and yield penalties are commonly reported, especially during the initial years following adoption (Achankeng and Cornelis, 2023; Corbeels et al., 2020; Pittelkow et al., 2015a). A global meta-analysis of 610 studies (Pittelkow et al., 2015a),



65 demonstrated the limitations of no-till when adopted alone, and how these limitations are reduced when it is combined with the other two pillars. The limited adoption of CA as a package results from complex biophysical, socioeconomic, and technical constraints. In small-scale farming systems, particularly in sub-Saharan Africa, for example, the main constraints include limited availability of (i.e., competing demand for) crop residues for permanent soil organic cover, and increased weed pressure under no-till (Corbeels et al., 2020; Giller et al., 2009). In high-input agricultural systems (e.g., Europe, United States), high requirements of herbicides and pesticides under CA, the need for machinery adapted for CA, and the associated costs are, some of the major barriers (Heller et al., 2024; Wade et al., 2015).

While CA practices generally offer net positive environmental benefits, both when adopted individually or as a package, their universal applicability across diverse biophysical and socioeconomic contexts remains highly debated due to inconsistent agronomic performance. In particular, achieving the core agronomic objective of CA – namely sustainable intensification, which is central to global food security and even critical to the livelihoods of farm households in developing countries, is challenging under CA practices such as no-till (Ceriani et al., 2026; Corbeels et al., 2020). For this reasons there is a growing need for identifying contexts where CA adoption is realistically effective rather than promoting it as a universal principle (Andersson and D’Souza, 2014; Descheemaeker et al., 2019; Giller et al., 2009; Pittelkow et al., 2015a; Pretty, 2018; Rodenburg et al., 2020). Sustainable intensification is achieved primarily through improvements in water and nutrient use efficiency. These efficiencies are influenced by interactions between climate, water, soil, and crop, and can be modified by changes in soil management practices in complex ways (Brouder and Gomez-Macpherson, 2014).

Table 1: Summary of changes in crop yields under CA practices observed in global meta-analyses. Statistically significant effects are indicated by an asterisk (*). Values in parentheses denote the number of observations contributing to each estimate.

Meta-analytic studies	Observed changes in crop yields				Coverage	Crop
	NT	RT	NT+RR	RT+RR		
(Pittelkow et al., 2015a)	-9.9 (287)*		-6.2 (1240)*		Global	Overall
(Sun et al., 2024)	-17.3 (302)*		-0.57 (781)		Global	Overall
(Cui et al., 2024)	-18.3 (126)*		-4.4 (802)*		Global	Maize, wheat
(Yang et al., 2022)	-6.1 (65)*	+0.8 (25)	+9.5 (53)*		Global	Overall
(Zhang et al., 2022)	-11.0 (137)*		-5.0 (429)		Global	Maize

Previous global (e.g., Cui et al., 2024; Pittelkow et al., 2015b; Sun et al., 2024) and regional (Ceriani et al., 2026; Corbeels et al., 2020; Van den Putte et al., 2010) meta-analyses have assessed agronomic performances of CA practices, all reporting overall yield reductions under no-till when is adopted alone (Table 1), although the magnitude and direction of effects vary across contexts. However, the biophysical mechanisms underlying these yield responses, particularly those driven possible



alterations in soil properties, have not been identified. Previous studies have also documented alterations in key soil physical and hydraulic properties under these practices, including bulk density, soil organic matter, infiltration capacity, and water retention (Blanchy et al., 2023b; Cui et al., 2024; Feifel et al., 2025; Reichert et al., 2009). Nevertheless, systematic evaluations linking these soil property changes to crop yield responses remain limited. Additionally, previous syntheses were largely focused on no-till or broadly defined conservation tillage, often without clearly distinguishing among different levels of conservation in terms of both tillage intensity and residue management for crop yield and soil properties. As a result, the effects of reduced tillage have been comparatively overlooked, particularly in earlier studies when considering the number of observations included (Table 1). Assessing the performances of different tillage intensity levels with residue management can provide a more robust basis for identifying suitable tillage intensity that can be combined with the two other pillars in a specific context.

In this study, we address these gaps using a global meta-analysis examining the effects of two of the CA pillars -- reduced soil disturbance, and residue retention -- on soil-plant-water relationships. Specifically, we assess how key soil physical properties (bulk density and organic matter content), soil water flow (saturated and near-saturated hydraulic conductivity), soil water retention and aeration (plant-available water capacity, wilting point, and air-capacity), mechanical properties (penetration resistance), and crop yield respond to both partial and combined adoption of reduced soil disturbance and residue retention. To reduce complexity, we excluded the third pillar (crop rotation) from this analysis. Crop rotation is generally easy to adopt, and typically provides net positive agronomic and environmental benefits (Xiao et al., 2025). Using conventional tillage without residue (CT) as a reference practice, we evaluate the performances of five CA practices, namely, no-till without residue (NT), reduced tillage without residue (RT), no-till with residue (NT+RR), reduced tillage with residue (RT+RR), and conventional tillage with residue retention (RR). The following questions guide our analysis: i) How do soil physical and hydraulic properties governing soil-plant-water relationships and crop yield differ under different CA practices? ii) How do these differences vary across pedoclimatic conditions and over time? iii) Which soil properties predominantly drive yield variability under these practices? Linking alterations in soil properties with differences in crop yield is critical for identifying the conditions in which CA for identifying the conditions in which CA can deliver positive outcomes for sustainable intensification and enhance adaptation to climate variability and change (Giller et al., 2011).

2. Methods

2.1. Data collection

To investigate the effects of conservation agriculture (CA) practices on soil-plant-water relationships and yield, we conducted a systematic literature search using the Web of Science database. The literature search was designed to capture studies reporting soil parameters that influence soil water movement, water retention and aeration, and accessibility of the water to plants, as well as crop yield under reduced soil disturbance (no-till and reduced tillage), and residue retention. The soil parameters that



regulate soil-plant-water relationships included in this analysis are described in Table 2. The search terms were defined from
125 key soil parameters, combined with terminologies related to CA practices as follows: TS = (“Bulk density” OR “infiltration”
OR “hydraulic conductivity” OR “field capacity” OR “water retention” OR “penetration resistance”) AND (“no tillage” OR
“zero tillage” OR “reduced tillage” OR “conservation tillage” OR “residue retention” OR “mulching”). Note that this is a
focused set of terms as less attention was given to variants and synonyms of the terminologies that would have otherwise
yielded an unmanageable number of records to be screened. The search was made by titles, abstracts, and keywords,
130 considering English-language literature (excluding review and conference papers) published over the last 30 years, from
January 1995 to October 2024. This resulted in a total of 2420 records.

We screened these records for suitability based on abstract review. During the screening stage, we employed Asreview Lab
(van de Schoot et al., 2021), an open source machine learning-aided screening tool that sorts articles by their relevance through
135 active learning over the course of the screening process. ASReview Lab has a reliable performance in terms of both prediction
of relevant studies and reduction in screening workload (van de Schoot et al., 2021), and has been widely applied in recent
systematic reviews and meta-analyses (e.g., Aschi et al., 2026; Lohmann et al., 2026; Wooster et al., 2026). After screening,
604 potentially relevant records were retained for full-text review. Subsequent screening and inclusion of records for data
extraction were based on the following criteria: i) the study reports on plot or field trial measurements comparing at least one
140 response variable (soil parameters and/or crop yield) under at least one CA practice -- no-till (NT) and/or reduced tillage (RT),
with and/or without residue retention (RR) -- with conventional tillage (CT) as a control; ii) the treatments are replicated or,
in case of on-farm field trials, duplicate measurements of the response variables were taken; iii) the number of replications of
the experimental and control groups are the same; iv) experimental and control groups were managed under comparable non-
experimental conditions such as fertilizer application, crop protection measures, rotation, and crop type, v) no duplicate studies
145 from the same site unless the reporting period or the measured response variables are different; vi) the location of the
experimental site is stated with known coordinates, or can be located from Google Maps. The full-text review resulted in 338
records that met the suitability criteria from which data were extracted. Data presented in graphical form were digitized using
PlotDigitizer (<https://plotdigitizer.com/>).



Table 2: Soil parameters regulating soil-plant-water relationships assessed in the meta-analysis. The main relationships comprise soil water movement, storage, plant-availability, soil aeration, and root growth. All measurements correspond to the plough layer (top 30 cm). No distinction was made between measurement methods used across studies.

Soil parameter	Key roles in soil-plant-water relationships
Bulk density (BD)	BD is strongly negatively correlated to the total porosity and reflects the soil compaction state. Compaction leads to poorer aeration, smaller hydraulic conductivities, smaller plant available water capacities, larger susceptibility for preferential flow and larger penetration resistances for roots (Widmer et al., 2025). Across the studies included, BD was predominantly measured using undisturbed soil samples collected by the core method (Blake and Hartge, 1986), in a few cases using disturbed samples (clod method).
Soil organic matter (SOM)	SOM serves as a binding agent that promotes the formation of soil aggregates, and provides a substrate for soil microbes and earthworms, which are crucial for soil burrowing, aggregate formation and stability alleviating compaction, and nutrient cycling (Hartmann and Six, 2023). It enhances plant water and nutrient use efficiency by improving water retention, flow and root growth (Hatfield et al., 2001). It is also an important source of nutrient for plants (Ranaivoson et al., 2017). Across the source studies, SOM was predominantly measured using wet oxidation (Walkley and Black, 1934), with some cases employing dry combustion methods.
Saturated and near-saturated hydraulic conductivity	Saturated hydraulic conductivity (K_s) facilitates infiltration through large pores while near-saturated hydraulic conductivity (K_h) enables soil water redistribution and drainage of excess water from pores larger than about $30\mu\text{m}$ (Jarvis, 2007). Across the studies considered, K_s was most measured using constant- and falling head methods, followed by ponded ring infiltration, whereas K_h was measured mainly using disc infiltrometers (Supplementary Fig. 1a-b).
Plant available water capacity (PAWC)	PAWC is the soil volume available to store plant-available water, held between field capacity (FC) and wilting point (WP). Soil water retention is commonly measured using a pressure plate apparatus, typically at pF 2.0 or pF 2.5 for FC and at pF 4.2 for WP.
Moisture content at wilting point (θ_{WP})	θ_{WP} is a threshold soil moisture content at and below which soil water is unavailable to plants and plants permanently wilt (Hillel, 1998).
Air-capacity (AC)	AC primarily comprises soil macropores (typically larger than $30\mu\text{m}$) available for air circulation when the soil is moist (at or below FC) but can become water-filled under wet soil conditions (Hillel, 1998). It is calculated as the difference between moisture content at saturation (θ_{sat}) and field capacity (θ_{FC}). In the studies reviewed, it was commonly measured using the table-pressure (sand box) method, in which saturated soil samples are subjected to tensions ranging from 0 and pF 2.0 or 2.5 depending on soil type. In some cases, θ_{sat} also assumed to be equal to total porosity.
Penetration resistance (PenR)	Measured using penetrometers, PenR represents the mechanical impedance of soil to root elongation, thereby regulating plant access to water and nutrients (Colombi et al., 2018). It varies strongly with soil moisture content. Consequently, the same soil type, particularly clayey soils, can exhibit high PenR values when dry, and much lower values when wet. The effect of PenR on root elongation also depends on its magnitude, with values exceeding $\sim 2\text{ MPa}$ generally considered to substantially restrict root growth (Bengough et al., 2011).

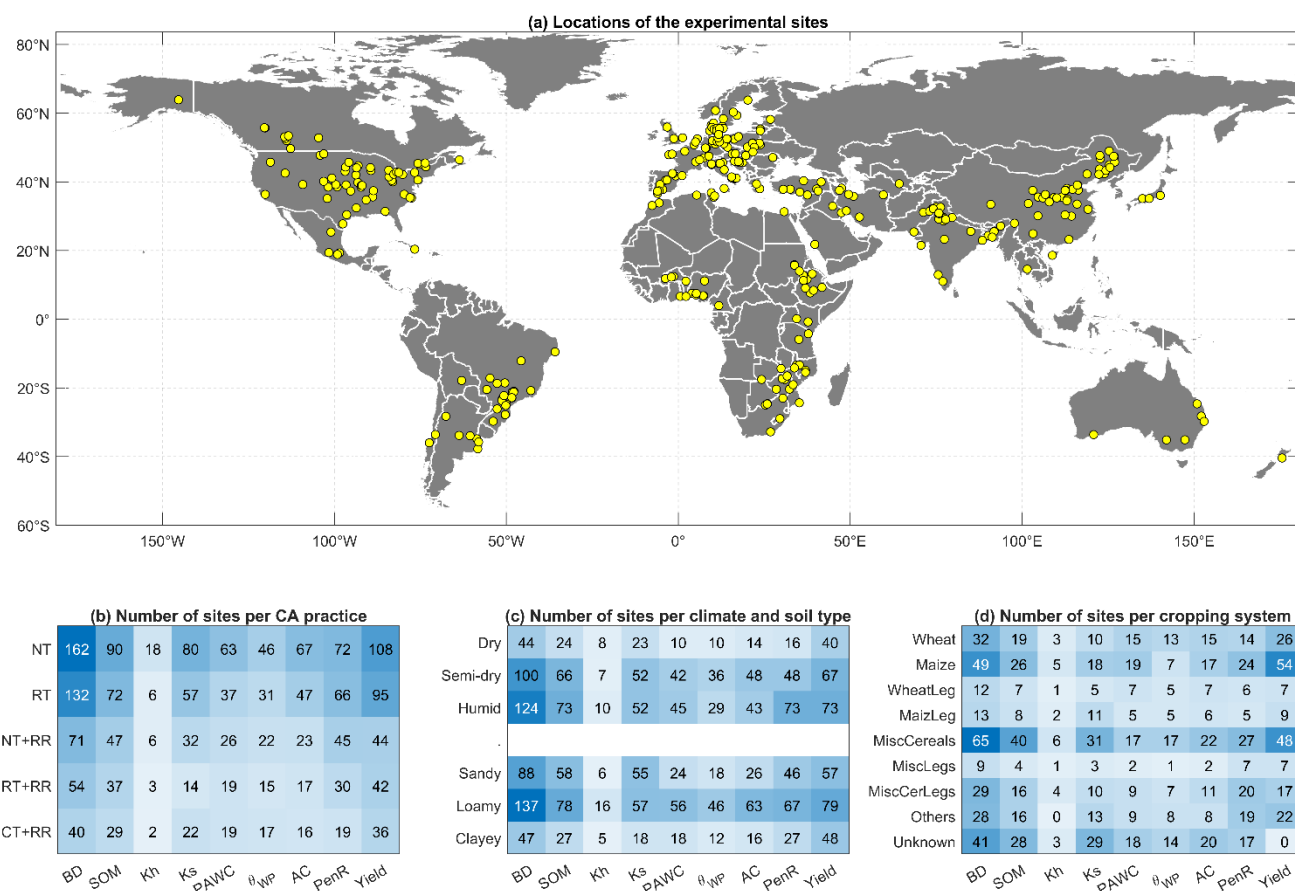


Figure 1: Overview of data included in the meta-analysis. a) Locations of experimental sites; b) Number of sites for which data on a response variable (soil properties and yield) are available per conservation agricultural practice; c) Number of sites for which data on a response variable are available per soil or climatic class; d) Number of sites for which data on a response variable are available per cropping system. NT = no-till with residue removed; RT = reduced tillage with residue removed; NT+RR = no-till with residue retained; RT+RR = reduced tillage with residue retained; CT+RR = conventional tillage with residue retained. BD = bulk density; SOM = soil organic matter; K_h = near-saturated hydraulic conductivity; K_s = saturated hydraulic conductivity; PAWC = available water capacity; θ_{WP} = moisture content at wilting point; AC = air-capacity; PenR = penetration resistance; WheatLeg = wheat-legume rotation; MaizLeg = maize-legume rotation; MiscCereal = miscellaneous cereals; MiscCerLegs = miscellaneous cereals-legume rotation.

2.2. The database

The resulting database contains records for 12 soil parameters and crop yield measured under paired conventional and conservation practices from 338 studies reporting observations at 361 experimental sites across 63 countries (Figure 1a). The recorded soil parameters include bulk density (BD) and porosity, organic matter content (SOM), steady state infiltration rate and cumulative infiltration capacity, saturated and near-saturated hydraulic conductivity, moisture content at saturation (θ_{sat}), moisture content at field capacity (θ_{FC}), moisture content wilting point (θ_{WP}), plant-available water capacity (PAWC), air-capacity (AC), and penetration resistance (PenR). Along with the soil parameters and yield, the database also contains key



metadata of the recorded observations. The experimental location, soil type, types of CA practices tested, duration of the practice, number of replications, as well as crop type and cropping system information for the soil parameters and yield considered in this analysis are shown in Figure 1b-c. For seven studies lacking information on soil type, we retrieved soil texture data from the Soil Grids (Poggio et al., 2021) database at the corresponding site locations. Because agroclimatic classifications of the experimental sites were not reported in most cases, we also integrated aridity index values for all sites from the Global Aridity Index version 3 database (Zomer et al., 2022). Five CA practices are documented in the database, namely: no-till with residue removed (NT), reduced tillage with residue removed (RT), no-till with residue retained (NT+RR), reduced tillage with residue retained (RT+RR), and conventional tillage with residue retained (CT+RR). Other conservation practices such as periodic no-till and cover cropping were excluded. Between-study differences in crop management such as fertilizer application were not explicitly considered. We also did not distinguish between irrigated and rainfed systems; however, in the discussion we assume that crop production in humid (aridity index, $AI > 0.65$) and semi-dry climates is predominantly rainfed, whereas in dry climates ($AI < 0.3$) it is predominantly irrigated.

Across the studies included, infiltration and hydraulic conductivity were reported in different forms (Supplementary Fig. 1a-c). Infiltration measurements were reported as initial infiltration (8.4% of recorded observations), cumulative infiltration (48.4%), final (steady state) infiltration (43.2%). Similarly, 73.7% of the hydraulic conductivity measurements corresponded to saturated hydraulic conductivity (K_s), 25.1% to near-saturated hydraulic conductivity (K_h), and only one study (Kreiselmeier et al., 2020) reported unsaturated hydraulic conductivity. These different forms reflect distinct soil water processes. Initial infiltration represents the soil surface response at the onset of rainfall or irrigation events and depends primarily on surface and near-surface soil structural conditions (e.g., cracks, surface crusting, porous layers and residues), as well as antecedent soil wetness. Hydraulic conductivity is primarily controlled by soil pore size distribution and connectivity, which govern the capacity of the soil to transmit water (Haruna et al., 2018). Well-connected large pores are associated with large K_s and play key role in partitioning rainfall into runoff and infiltration. When rainfall intensity or irrigation rate is smaller than K_s , flow is increasingly governed by K_h at matric tension heads of 0 to 100mm and controls soil moisture replenishment, redistribution, and (Blanchy et al., 2023b; Kuhlmann et al., 2012). Final infiltration (I_f) represents steady soil water flow and is often used as a proxy for field K_s , particularly when measured under approximately one-dimensional flow conditions such as the double ring infiltrometer (Wu et al., 1999). This relationship is reflected in our database where K_s and I_f from simultaneous observations under control experiments (conventional tillage) in 12 studies, are strongly correlated (Pearson's $r = 0.82$). In our analysis, we therefore combined K_s observations from 66 studies with I_f observations from 39 in which K_s was not reported, to represent saturated soil hydraulic conductivity. Despite limited data availability, we also analysed near-saturated soil hydraulic conductivity separately to represent soil water replenishment, redistribution and drainage processes, based on K_h observations from 21 studies.



2.3. Data preparation

We analysed effects of CA practices on soil parameters (BD, SOM, K_h , K_s , PAWC, θ_{WP} , AC, and PenR) and crop yield based on log-transformed response ratio ($\ln RR$). For each observation, $\ln RR$ was calculated as (Adams et al., 1997):

$$\ln RR = \ln \left(\frac{X_E}{X_C} \right) \quad (1)$$

where X_E is the reported mean value of the experimental observation under the CA practice for which the effect was evaluated, and X_C is the corresponding mean control observation value under conventional tillage with residue removed (CT). Values of $\ln RR$ were then weighted according to the number of treatment or measurement replications of the observation in each study, such that observations derived from larger sample sizes received greater weight in the estimation of overall effects, under the assumption that they are more robust than those derived from smaller sample sizes (Adams et al., 1997). Ideally, these weights are calculated from within-study variances of the reported mean observations; however, as witnessed in previous meta-analyses (Achankeng and Cornelis, 2023; Pittelkow et al., 2015a), these variances were not available for a large number of studies included in the data extraction. Therefore, following previous works (Adams et al., 1997; Pittelkow et al., 2015a; Zhao et al., 2022), we calculated the within-study ‘variance estimate’ used for weighting each observation based on the number of replications as:

$$v_i = \frac{N_E + N_C}{N_E N_C} \quad (2)$$

where N_E and N_C are the number of the replications of the experimental and control treatments, respectively. When multiple observations were drawn from the same site per response variable under each practice, variance estimates were divided by the number of observations for that response variable (Borenstein et al., 2010; Pittelkow et al., 2015a). Prior to effect size estimation, data quality was assessed. Publication bias was evaluated based on visual inspection of asymmetry in funnel plots (Sterne and Egger, 2001), and no substantial indications of biases were detected. We removed outliers from the data by excluding data points with $\ln RR$ values exceeding five standard deviations from the mean (Pittelkow et al., 2015a). Outliers were observed only in the no-till and reduced tillage data for three response variables and accounted, on average, for 1.4% of bulk density observations, 2.3% of penetration resistance observations, and 0.8% of yield observations.

2.4. Estimation of mean effect sizes

We used a random-effects meta-analytic model implemented in the *metafor* package (Viechtbauer, 2010) in R to estimate the mean effect sizes for each response variable under the different CA practices. In this model, the observed effect size y_i (i.e., $\ln RR$) is modelled as:

$$y_i = \mu + u_i + e_i \quad (3)$$



where μ is the mean effect size, $u_i \sim N(0, \tau^2)$ represents the in-between-study variance (heterogeneity), and $e_i \sim N(0, v_i)$ is the sampling error. The true effect size is assumed to follow a normal distribution with mean μ and variance τ^2 . The log-transformed response ratios of our data largely satisfy this assumption for all variables considered (Supplementary Fig. 2). We implemented the maximum-likelihood estimator “ML” in the *metafor* package to determine heterogeneity. The estimate of μ is obtained using weighted least squares with weights calculated as the inverse of the total variance estimates (Viechtbauer, 2010):

$$w_i = \frac{1}{v_i + \hat{\tau}^2} \quad (4)$$

where $\hat{\tau}^2$ is the ML estimate of between-study heterogeneity. In our application, we also included site location ID as a random effect to account for the correlation structure among observations originating from the same site. The model default Wald-type significance test which is based on the test statistic Z, and the 95% confidence intervals were used to assess whether the estimated mean effect sizes were significantly different from zero at $\alpha = 0.05$.

Effect size analyses were conducted at two levels. First, all observations under each CA practice were analyzed to quantify the overall effects of the practices on soil parameters and crop yield. Second, the data were subset by climate classes, soil textural classes, and practice duration, and analyses were repeated within each subset to assess context-specific and temporal effects. Climatic conditions were classified based on aridity index (AI) as *dry* ($AI \leq 0.3$), *semi-dry* ($0.3 < AI \leq 0.65$), and *humid* ($AI > 0.65$). Soil textural classes were regrouped as *sandy* (includes sand, sandy loam, loamy sand, and sandy clay loam), *loamy* (loam, silty loam, clay loam, silty clay loam, and silt), and *clayey* (sandy clay, clay and silty clay); and the duration of the CA practice was categorized as *1-3 years*, *4-9 years*, and *>10 years*. In all cases, only subsets containing at least five studies were analysed. To assess trends in overall effects across climatic, soil textural, and temporal gradients, we conducted meta-regression analyses using each factor as a moderator. We also performed preliminary analyses to test for potential interaction effects among moderators; however, no significant interactions were detected, and they were therefore not considered further. Estimated overall effect sizes and confidence intervals were back-transformed and expressed in percentages. The statistical significances of the changes were presented based on p-values. In our reporting and discussions of the results, we have also adopted a gradual (continuous) interpretation of evidence rather than a binary reliance on statistical significance alone (Amrhein et al., 2019; Muff et al., 2022). We define three effect levels: *neutral* (non-significant changes of magnitudes $<5\%$), *weak* (non-significant changes with magnitudes $\geq 5\%$), and *robust* (statistically significant changes).

2.5. Crop yield sensitivity to soil parameters

To assess key drivers of yield variability under various CA practices, we performed a sensitivity analysis and examined the relative importance of each soil parameter. Both sensitivity and relative importance were analysed using univariate linear mixed-effect models (LME) of yield versus each soil parameter. We fitted an LME model with $\ln RRR$ of yield as a response variable, $\ln RRR$ of individual soil parameter as a predictor variable, and experimental site ID as a random effect. We used



univariate LME because crop yield and multiple soil parameters are rarely measured concurrently at the same experimental site. For this reason, only sites at which crop yield and a soil parameter were simultaneously measured were included in each analysis. For the two main practices, no-till and reduced tillage, the number of sites with concurrent measurements of crop yield and soil parameters varied on average from 68 for bulk density to 15 for water retention at wilting point.

Sensitivity was used to estimate ‘influence’ – namely, the yield response to a unit change in a given soil parameter, with the aim of identifying critical soil properties that should be considered when making decisions regarding the adoption, and implementation of CA practices. We quantified sensitivity using absolute values of the fixed-effect regression coefficient (slope), β , of the LME model (Saltelli and Ratto, 2008). To ensure comparability across soil parameters, we calculated a relative sensitivity index (SI) as:

$$SI = \frac{|\beta_k|}{|\beta|_{max}} \quad (5)$$

where β_k is the regression slope of the fitted univariate LME model of yield versus the k^{th} soil property ($k = 1, 2, 3, \dots, 7$), and β_{max} is the largest slope observed among all soil parameters included. The actual impact of alterations in soil parameters on yield depends on the magnitude of the alteration and sensitivity of yield to these alterations. We calculated relative ‘importance’ (RI) to estimate the actual impact of change in each soil parameter on observed yield variability. RI was quantified using standardized regression coefficient, which combines the magnitude of the regression slope and the variability of the predictor relative to that of the response variable, $\ln RR$ of yield (Grömping, 2006; Saltelli and Ratto, 2008):

$$RI = |\beta_k| \times \frac{\sigma_{x,k}}{\sigma_y} \quad (6)$$

where σ_x and σ_y denote the standard deviations of the predictor ($\ln RR$ of the k^{th} soil property) and the response variable ($\ln RR$ of yield), respectively. Both SI and RI values range from 0 (no sensitivity or importance) to 1 (highest sensitivity or importance).

3. Results

3.1. Changes in soil organic matter, bulk density, and penetration resistance

Reduced soil disturbance (NT and RT), and residue retention (RR), generally increased SOM content (Figure 2b). Significant SOM increases were observed under NT (+15.5%, $p = 0.006$), NT+RR (+27.3%, $p = 0.005$), and CT+RR (+31.2%, $p = 0.01$). In contrast, soil bulk density exhibited high variability among studies, and showed no significant changes (Figure 2a). However, when mean effect sizes were meta-regressed along the gradient of increasing ‘tillage intensity and residue retention’ (i.e. NT $\rightarrow$ RT $\rightarrow$ NT+RR $\rightarrow$ RT+RR $\rightarrow$ CT+RR), hereafter referred to as TIRR, mean effect sizes tended to decrease consistently with increasing TIRR across the gradient. Despite relatively small and weak mean effects on bulk density, both NT and RT were associated with overall increases in penetration resistance (PenR) (Figure 2h). Irrespective of residue

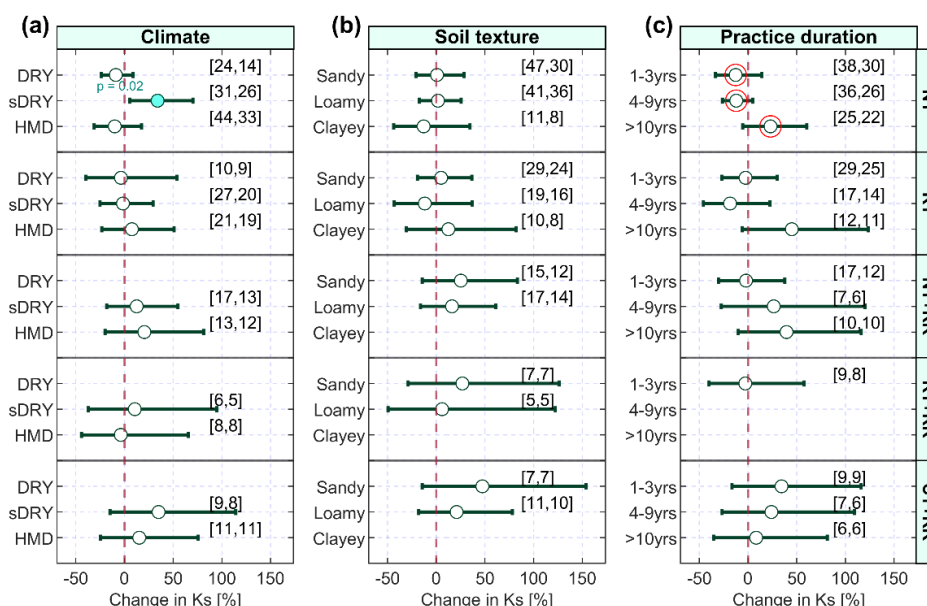


management, PenR significantly increased by 29.4% ($p < 0.001$) under NT and by 24.1% ($p < 0.001$) under RT (Table 3). However, effects decreased with increasing TIRR ($p < 0.001$), consistent with the pattern observed for bulk density (Figure 2a,h). Significant increases in penetration resistance occurred when residues were removed, with mean effects of +39.6% under NT ($p < 0.001$) and +28.0% under RT ($p < 0.001$). The largest increases in penetration resistance were observed in the top 10 cm, with effects decreasing with depth across the plough layer (Supplementary Fig. 3). Effect analysis by climatic and soil conditions (see Supplementary Fig. 3a-c) revealed that under NT, increases in penetration resistance were particularly pronounced in dry (+37.8%, $p = 0.045$) and humid (43.2%, $p = 0.001$) climates, and in loamy (34.5%, $p = 0.006$) and sandy soils (56.1%, $p = 0.002$). When effects were analysed by the duration of CA implementation, significant increases in penetration resistance occurred during the first 1-9 years. Under RT, significant increases occurred in humid climates, sandy soils, and during the first 3 years after adoption.



3.2. Effects on saturated and near-saturated hydraulic conductivity

The cascading effect of the observed overall increase in soil bulk density under reduced soil disturbance, although relatively weak, were reflected in saturated and near-saturated soil hydraulic conductivities (Figure 2c-d). Regardless of residue retention, near-saturated hydraulic conductivity (K_h) decreased significantly under NT (-26.9%, $p = 0.01$). Similar but relatively weaker effect was also observed RT (-21%, $p = 0.15$) (Table 3). Under NT, reductions in K_h were larger and statistically significant manifested in dry (Aridity index, $AI < 0.3$) and humid ($AI > 0.65$) climates, whereas effects were weak negative in semi-dry climates. Patterns of variation in K_h responses across climate, soil texture, and duration to the different CA practices were unclear because of limited data availability. In contrast, both NT and RT showed overall neutral effects on saturated hydraulic conductivity (K_s) (Figure 2d). However, under NT, effects on K_s were weak negative dry and humid climates (Figure 3a), whereas a robust positive effect was observed in semi-dry climates (34%, $p = 0.017$). The influence of soil texture on K_s was not consistent across the CA practices, except in clay soils, where NT without residue retention showed a weak negative effect (-19%, $p = 0.23$) (Figure 3b). Nevertheless, K_s generally improved with practice duration, particularly under NT (trend $p = 0.003$).



335

340

Figure 3: Changes in saturated hydraulic conductivity (K_s) under reduced soil disturbance and residue retention. Effects of no-till (NT) and reduced tillage (RT), with (+) and without residue retention (RR) relative to conventional tillage (CT), are shown across climatic conditions (a), soil types (b), and durations of practice (c). Climate classes were defined by the aridity index (AI) as dry (DRY; $AI < 0.3$), semi-dry (sDRY; $0.3 < AI \leq 0.65$) and humid (HMD; $AI > 0.65$). Mean effects (expressed in %) quantified using the random-effects meta-analytic model (metafor package in R), are shown by circles, with horizontal bars representing 95% confidence intervals. Cyan-filled circles show statistically significant effects. Red circles indicate statistically significant trends in the effects along gradients of climatic, soil texture or duration moderators. Dashed red vertical lines represent no effect relative to CT. Numbers



345 **in square brackets indicate the number of observations (first) and studies (second) included in each analysis. Only results based on observations from at least 5 studies are shown.**



Table 3: Effects of no-till (NT) and reduced tillage (RT) by climate, soil type, and duration, on practice for soil properties -- bulk density (BD), soil organic matter (SOM), near-saturated hydraulic conductivity (Kh), saturated hydraulic conductivity (Ks), plant-availability water capacity (PAWC), water retention at wilting point (θ_{WP}), air-filled porosity (AFP), and penetration resistance (PenR) – irrespective of residue management, based on random-effects meta-analytic model. Statistically significant effects at $\alpha = 0.05$ are indicated by an asterisk (*). Blank cells under Kh indicate categories for which observations were insufficient (fewer than five studies).

	SOM			Kh			Ks			PAWC			θ_{WP}			AFP			PenR			Yield		
	Effect (%)	p-val	Effect (%)	p-val	Effect (%)	p-val	Effect (%)	p-val	Effect (%)	p-val	Effect (%)	p-val	Effect (%)	p-val	Effect (%)	p-val	Effect (%)	p-val	Effect (%)	p-val	Effect (%)	p-val		
NT	19.1*	0.00	-26.9*	0.01	4.19	0.53	2.3	0.65	3.6	0.53	-19.0*	0.00	29.4*	0.00	-5.7*	0.02								
Dry	38.8*	0.00	-29.4*	0.05	-6.14	0.45	4.8	0.65	-3.3	0.74	-14.4	0.12	19.2	0.20	-7.1*	0.02								
Semi-dry	12.6	0.14	-4.41	0.90	26.10*	0.01	7.5	0.52	15.9	0.21	-31.7*	0.00	27.7*	0.00	3.1	0.56								
Humid	15.4*	0.03	-31.2*	0.04	-2.79	0.81	-0.3	0.96	2.6	0.76	-13.3	0.06	34.0*	0.00	-6.8*	0.00								
Sandy	18.6*	0.03	-35.9	0.10	7.67	0.48	12.4	0.22	-2.9	0.77	-25.3*	0.00	38.3*	0.00	-2.3	0.30								
Loamy	19.2*	0.00	-23.5	0.07	7.67	0.36	-1.7	0.78	5.8	0.44	-18.8*	0.02	29.2*	0.00	-6.7	0.08								
Clayey	11.9	0.43			-19.52	0.26	1.8	0.90	14.4	0.49	-17.4	0.24	18.4	0.12	-13.0*	0.02								
1-3yrs	12.1	0.12			-8.17	0.43	-0.2	0.98	1.3	0.91	-15.1	0.07	23.9*	0.01	-11.1*	0.00								
4-9yrs	23.4*	0.00	-17.7	0.39	-7.22	0.36	3.6	0.73	10.3	0.41	-30.1*	0.00	41.4*	0.00	-1.9	0.58								
>10yrs	23.6*	0.03	-15.7	0.33	28.33	0.01	3.1	0.71	0.7	0.94	-8.9	0.27	9.2	0.41	1.6	0.73								
RT	8.2	0.12	-21.0	0.15	3.25	0.68	0.9	0.89	0.9	0.91	-3.9	0.53	24.1*	0.00	-4.0	0.24								
Dry	15.3	0.32	-24.7	0.14	0.12	1.00	-0.2	0.99	4.7	0.86	2.5	0.91	13.0	0.62	-11.2*	0.03								
Semi-dry	7.8	0.44			7.04	0.57	4.7	0.74	4.2	0.78	-11.6	0.37	11.6	0.24	-7.6	0.26								
Humid	6.9	0.31			0.13	0.99	-0.1	0.99	-0.9	0.92	-2.2	0.76	33.4*	0.00	0.4	0.94								
Sandy	8.0	0.43	13.9	0.25	12.61	0.27	5.5	0.74	6.1	0.78	-6.3	0.70	35.3*	0.00	0.2	0.97								
Loamy	7.9	0.26	-20.5	0.36	-5.29	0.74	-0.6	0.94	0.1	0.99	-3.9	0.56	21.2*	0.01	-4.4	0.26								
Clayey	9.9	0.48	-20.3	0.50	-6.40	0.71	5.1	0.81	-0.7	0.98	5.8	0.85	12.7	0.44	-11.4	0.14								
1-3yrs	6.3	0.45			-0.62	0.95	-1.7	0.86	9.9	0.53	-5.5	0.61	24.5*	0.02	-4.1	0.26								
4-9yrs	10.5	0.28			-16.38	0.27	-0.9	0.95	2.3	0.89	-2.2	0.87	25.0*	0.03	-3.8	0.62								
>10yrs	10.1	0.45			37.45*	0.05	8.6	0.46	-6.3	0.56	0.3	0.98	17.8	0.19	1.4	0.86								



3.3. Effects on soil water retention and aeration capacity

Overall effects of reduced soil disturbance and residue management on plant-available water capacity and wilting point varied across the studies, with no significant mean effects observed (Figure 2e-f). Responses also showed little variation across climates and soil type, and no clear pattern of effects by practice duration was detected (Supplementary Fig. 5a-c). In contrast, reduced soil disturbance was generally associated with declines in soil air capacity (AC). NT significantly reduced AC overall (18.6%, $p < 0.001$), although the magnitude of this reduction slightly decreasing along the gradient of increasing TIRR (Figure 2g, Table 3). The magnitude of AC reductions varied with climate and soil type. Robust declines under NT were predominantly observed in semi-dry (-25.1%, $p = 0.05$) and in humid (-16.1%, $p = 0.021$) climates (Supplementary Fig. 6a). When analysed by soil type, the largest reductions (-27.9%, $p < 0.001$) occurred in sandy soils followed by clayey soils, although the latter effect was weak (-15.5%, $p = 0.341$) (Supplementary Fig. 6b).

To further illustrate how reduced soil disturbance alters soil pore redistribution and, consequently, soil water retention and aeration capacity across textural classes, we compared absolute changes in water retention capacities at saturation (θ_{Sat}), field capacity (θ_{FC}), and wilting point (θ_{WP}), under no-till and reduced tillage, with those under conventional tillage, using observations from our database (Figure 4). No-till, regardless of residue management, generally increased water retention at both θ_{FC} and θ_{WP} in sandy loam and all finer-textured soils (Figure 4a). At the same time, no-till reduced θ_{Sat} in sandy, sandy loam, loamy and clayey soils, resulting in reduction in the aeration pore space. In contrast, these changes were minimal under reduced tillage (Figure 4b).

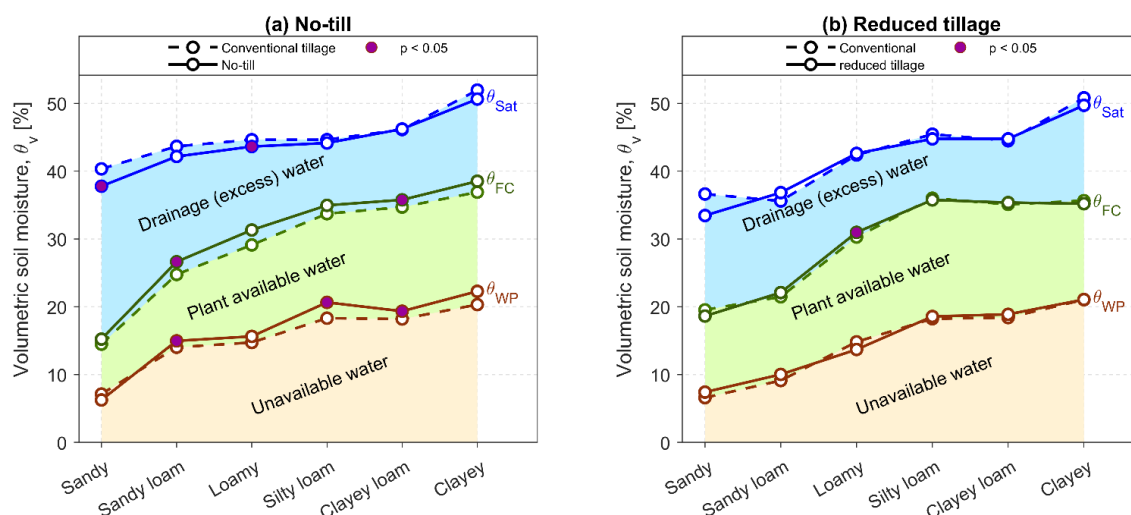


Figure 4: Soil moisture retention and aeration capacity under no-till and reduced tillage practices relative to conventional tillage. Moisture constants -- volumetric moisture content at saturation (θ_{Sat}), field capacity (θ_{FC}), and wilting point (θ_{WP}) -- that together define drainage water, available water, and unavailable water were compiled using observations reported across studies. Changes in these soil moisture regimes are shown for no-till (NT) in (a) and reduced tillage (RT) in (b) relative to the control practice, conventional tillage (CT), across six soil textural classes. Comparisons were made irrespective of residue management for both NT and RT (solid lines), and for CT with residue removed (dashed lines). The number of observation and studies included in these illustrations, respectively, are as follows: θ_{Sat} [127,82], θ_{FC} [120,78], and θ_{WP} [88,61] for NT, and θ_{Sat} [69,47], θ_{FC} [67,44], and θ_{WP} [55,40] for RT. Significant changes ($p < 0.05$) are indicated by purple-filled circles.

3.4. Crop yield responses

Overall, crop yield was negatively affected by NT (mean -6.1%, $p = 0.024$) (Figure 2h). In contrast, yield reductions decreased at a significant trend ($p = 0.041$) with increasing TIRR (Figure 5a). Moreover, yield responses varied substantially with climate, soil type, and practice duration, particularly under NT, NT+RR, and RT. Under NT, yield increased significantly in semi-dry climates (+16.3%, $p = 0.004$) but declined by 7.3% ($p < 0.001$) in humid climates, and by 8.3% ($p = 0.038$) in dry climates where irrigation is expected to dominate (Figure 5a). Soil texture had strong influences on yield responses. The highest yield reductions were pronounced in clayey soils under NT (-19.2%, $p = 0.124$), and RT (-19.3%, $p = 0.047$) (Figure 5b), although effect was statistically insignificant under NT. Across these practices, yield reductions generally decreased along the soil textural gradients, from substantial yield reductions in clayey soils to weak negative response under NT (-5.3%, $p = 0.077$), and weak positive response under RT and NT+RR in sandy soils. Under NT, regardless of residue management, yield penalties decreased with duration after adoption (Figure 5c). During the first 1-3 years following adoption, NT significantly reduced yield by 11.8% ($p < 0.001$), whereas reductions diminished after 10 years. With residue retention, NT transitioned from an initial yield reduction (-9.2%, $p = 0.075$) during the first 1-3 years to a robust yield improvement (10.3%, $p = 0.045$) after 10

years of implementation. In contrast, practice duration had no clear effect on yields under reduced tillage, regardless of residue management.

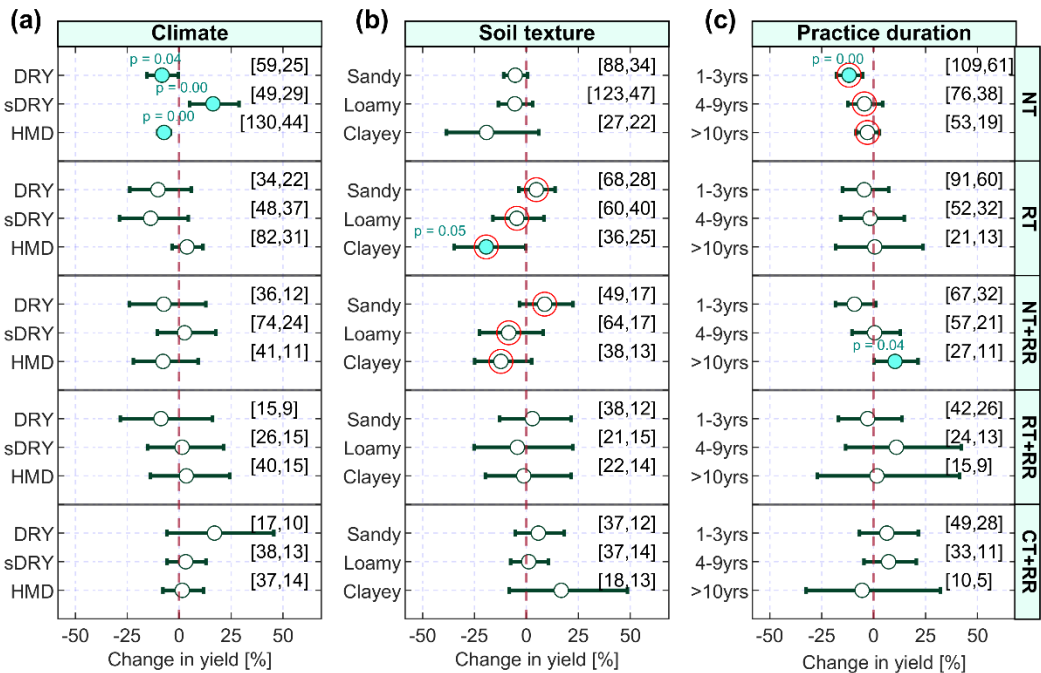


Figure 5: Yield responses to reduced soil disturbance and residue retention. Effects of no-till (NT) and reduced tillage (RT), with (+) and without residue retention (RR) relative to conventional tillage (CT), are shown across climatic conditions (a), soil types (b), and durations of practice (c). Climate classes were defined by the aridity index (AI) as dry (DRY; AI < 0.3), semi-dry (sDRY; 0.3 < AI ≤ 0.65) and humid (HMD; AI > 0.65). Mean effects (expressed in %) quantified using the random-effects meta-analytic model (metafor package in R), are shown by circles, with horizontal bars representing 95% confidence intervals. Cyan-filled circles show statistically significant effects. Red circles indicate statistically significant trends in the effects along gradients of climatic, soil texture or duration moderators. Dashed red vertical lines represent no effect relative to CT. Numbers in square brackets indicate the number of observations (first) and studies (second) included in each analysis. Only results based on observations from at least 5 studies are shown.

3.5. Crop yield sensitivity to soil parameters

Crop yield showed high sensitivity to changes in soil bulk density across all five conservation practices (blue bars, Figure 6), with statistically significant slope particularly under NT, RT and CT+RR (See Supplementary Table 1 for mixed-effects regression slopes and p-values). However, because the variability in effect sizes of bulk density is smaller than that of crop yield effect sizes across sites and observations (Supplementary Fig. 7), its contribution to observed yield variability, expressed as relative importance (RI), orange bars in Figure 6, was comparatively low. In contrast, influences and relative importance of other soil properties varied among CA practices. Under NT, wilting point (θ_{WP}) followed by available water capacity (PAWC),



415 and saturated hydraulic conductivity (K_s) showed high SI for yield (Figure 6a). Mean response curves derived from back-transformed linear mixed-effects model simulations (Supplementary Fig. 8) indicate that changes in θ_{WP} exhibit a non-linear negative relationship with yield variation, whereas both PAWC and K_s show linear positive relationships with yield variation. Yield was least sensitive to soil organic matter (SOM), air-capacity (AC), and penetration resistance (PenR) under NT. In terms of importance, PAWC, θ_{WP} , K_s , and PenR ranked as the top four possible drivers of observed changes in yield among
420 the evaluated soil properties. Under RT, no soil parameter other than bulk density exhibited statistically significant regression slope, although SI and RI remained relatively high for θ_{WP} (Figure 6b). Examination of the mean response curves relating changes in bulk density to yield across different soil types revealed non-linear negative relationships, with sensitivity decreasing from clayey to sandy soils under both NT and RT (Supplementary Fig. 9).

When NT and RT were combined with residue retention, K_s , emerged as a significantly influential and the most important
425 driver of change in yield under these practices (Figure 6c). Interestingly, the influence and relative importance of SOM increased with increasing TIRR, with significant influence and importance observed under RT+RR and CT+RR (Figure 6d, e). These results indicate a shift in the influence and relative importance of soil parameters across the TIRR spectrum (Figure 6a-e). Under NT, yield responses were primarily associated with soil parameters responsible for soil water retention (PAWC and θ_{WP}), and partly with soil water movement through large pores (K_s), and to a lesser extent (but still statistically significant),
430 with root growth conditions (PenR). These influences are weak under RT, where effects of changes in bulk density on soil-plant-water relationship were no longer statistically significant. Instead, when reduced soil disturbance was combined with residue retention (i.e., under NT+RR and RT+RR), dominant influence and relative importance shifted toward K_s and SOM. The influence of AC was also significant under RT+RR. When conventional tillage was combined with residue retention (CT+RR), yield variability was mainly associated with soil structural properties, particularly bulk density and SOM, indicating
435 diminished effects of no-till and reduced tillage on soil-plant-water interactions.

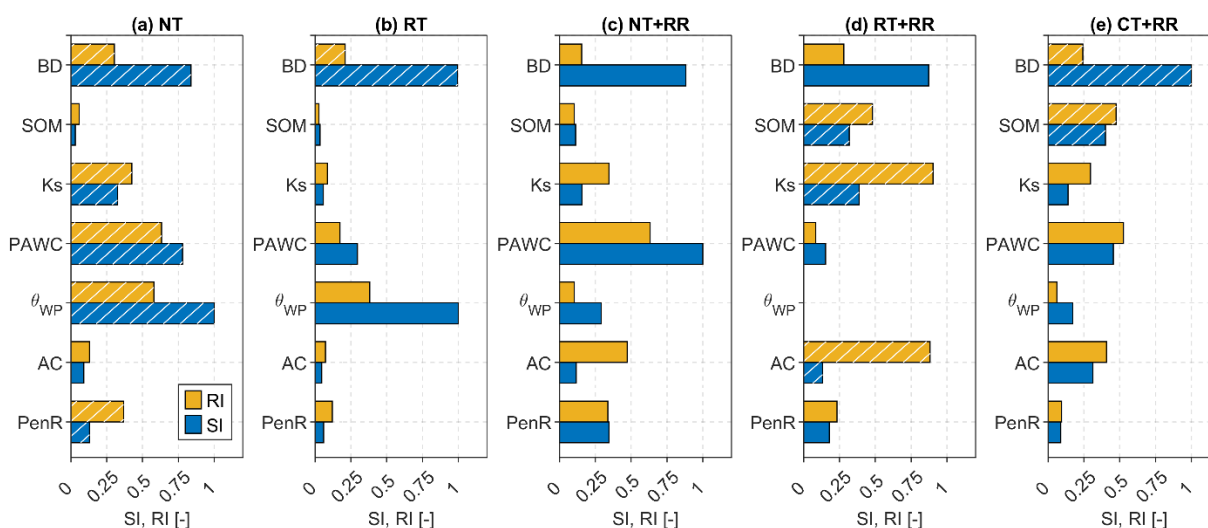


Figure 6: Crop yield sensitivity and relative importance of soil properties under reduced soil disturbance and residue retention. Sensitivity indices (SI) and relative importance (RI) were determined using univariate linear mixed-effects regression coefficients fitted to log-transformed response ratios (lnRR) of yield versus individual soil parameters (BD: bulk density, SOM: soil organic matter, K_s : saturated hydraulic conductivity, PAWC: plant-available water capacity, θ_{WP} : moisture content at wilting point, AC: air capacity, and PenR: penetration resistance) under (a) no-till (NT) without residue, (b) reduced tillage without residue (RT), (c) no-till with residue (NT+RR), (d) reduced tillage with residue (RT+RR), and (e) conventional tillage with residue (CT+RR). Hatched bars show SI and RI derived from statistically significant ($p < 0.05$) univariate linear mixed-effects regression coefficients.

4. Discussion

4.1. Overall agronomic performance across conservation agricultural practices

In conventional agriculture, tillage is a vital soil management practice that provides several important benefits, including temporary alleviation of soil compaction by loosening the plough layer thereby creating favourable conditions for root growth, water and nutrient uptake; incorporation and oxidation of organic matter to facilitate nutrient cycling; and control of weeds, pests, and disease (Hobbs et al., 2008). In CA where tillage is reduced or avoided, most of these benefits are expected to be achieved through organic soil cover and crop rotation (Kassam et al., 2009). The steady increase in yield penalties with decreasing tillage intensity and residue retention (TIRR) observed in this analysis (Figure 5a) indicates the agronomic trade-offs associated with partial adoption of CA practices, particularly reduced soil disturbance without residue retention. Previous global meta-analyses summarized in Table 1 show similar response patterns – significant yield reductions ranging from -18.3% (Cui et al., 2024) to -9.9% (Pittelkow et al., 2015a) under reduced soil disturbance without residue retention, especially NT, and diminished negative effects ranging from -6.2% (Pittelkow et al., 2015a) to neutral effects (Sun et al., 2024) when residue retention is combined with reduced disturbance. Consistent with this range, our findings also show mean yield reductions of 6.1% ($p < 0.05$) under NT alone, and 3.5% ($p > 0.05$) when NT is combined with residue retention.

As expected, mean yield reductions were smaller under RT than under NT and diminished further when RT was combined with residue retention (Figure 5a). Consistent with this pattern, Van den Putte et al. (2010) reported average yield reductions of 8.5% under no-till and 2.7% under reduced tillage across Europe. In contrast, Zhang et al. (2022) reported nearly similar mean yield reductions of about 5% under NT and RT. Although these responses vary substantially depending on contexts, our analysis indicates that on average RT+RR results in a largely neutral yield response, whereas CT+RR is generally associated with yield gains (Figure 7a). Similar patterns were reported by Yang et al. (2022), who observed about 6% overall yield reduction under NT, a neutral yield response under RT, and significant yield gains of about 9.5% with residue returned, although their analysis was based on a relatively small number of observations compared to other global meta-analyses (see Table 3). Least-squares fit to the observed mean changes in yield and soil properties across the five CA practices evaluated (Figure 7a), showed that lower tillage intensity, especially without residue retention, was associated with greater yield declines.

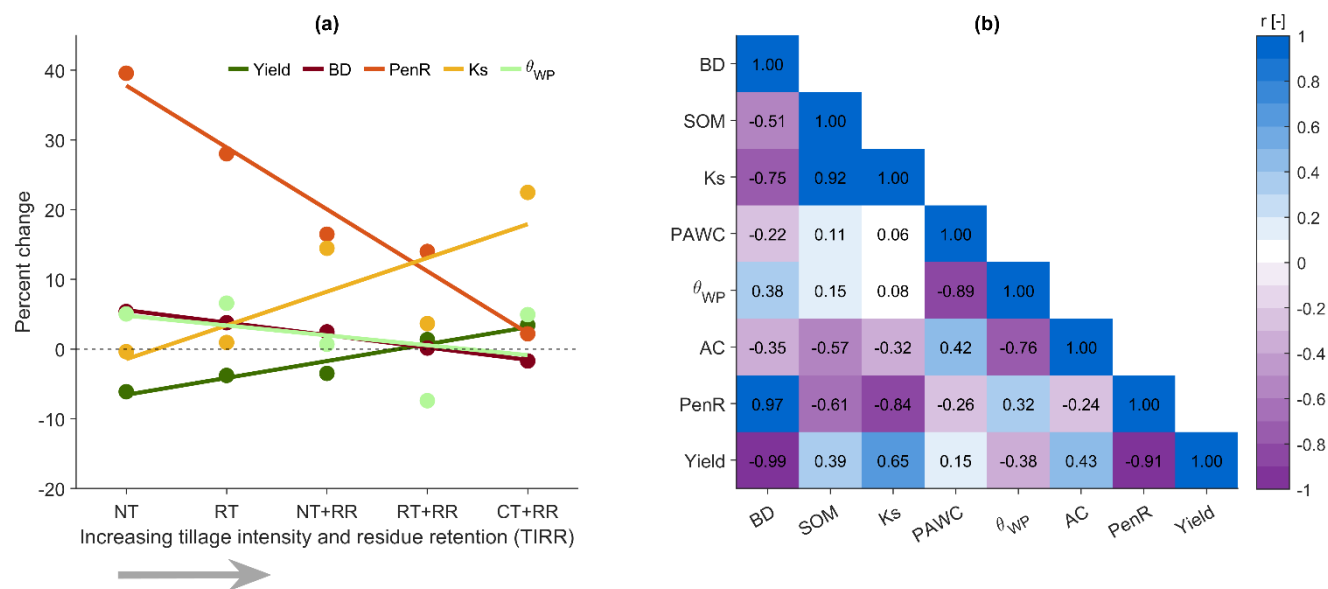


Figure 7: Global trends and co-variability of crop yield and soil physical, hydraulic and mechanical properties along increasing tillage intensity and residue retention (TIRR). a) Mean changes in yield, bulk density (BD), saturated hydraulic conductivity (K_s), penetration resistance (PenR), and water retention at wilting point (θ_{WP}) across conservation agricultural practices: no-till (NT), reduced tillage (RT) without and with (+) residue retention (RR), and conventional tillage with residue retention (CT+RR), relative to CT without RR. Mean effects (shown by circles) were estimated using random-effects meta-analytic model applied to all observations within each practice. b) Correlation matrix showing the relationships among soil properties and crop yield across the TIRR gradient.



4.2. Relationship between changes in soil properties and yield responses

4.2.1. Responses across practices

The overall yield responses observed along the gradient of increasing TIRR (Figure 7a) are closely associated with compaction-driven changes in soil physical, hydraulic, and mechanical properties. Mean yield responses across the TIRR gradient mirrored mean changes in bulk density (Pearson's $r = -0.99$; Figure 7b), although bulk density responses highly varied across studies, and the trend in changes in bulk density was not statistically significant (Figure 7a). The functional effects of compaction are clearly reflected in changes in penetration resistance ($r = -0.91$), which captures possible mechanical constraints to root growth. However, yield is relatively less sensitive to changes in penetration resistance (Figure 6). This likely reflects the fact that effects of PenR on root growth depends on its magnitude, and vary with soil moisture content (Colombi et al., 2018; Suzuki et al., 2013). Under moist soil conditions, roots can penetrate more easily through dense soil matrix that disconnect soil macropores in compacted soils, compared with dry conditions. In general, PenR values of 2 MPa or higher are often considered critically limiting for root growth (Bengough et al., 2011; Peixoto et al., 2019a; Suzuki et al., 2013). In our database, among observations reporting PenR together with crop yields, ~23% of soils under conventional tillage (control) practice and ~32% of soils under RT and NT treatments exceeded this threshold.

While effects of soil compaction on yield, certainly, vary with factors such as soil type, climatic conditions, duration of practice, and machinery loads, this remains one of the major barriers for CA adoption (Heller et al., 2024). In countries where NT has been widely adopted, such as Brazil and Argentina, compaction challenges are increasingly reported under continuous no-till systems (Peixoto et al., 2019b; Peralta et al., 2021). For example, a meta-analysis of data from the Pampas region of Argentina (Peralta et al., 2021) demonstrated that the introduction of non-inversion tillage (reduced tillage) as a compaction alleviation measure led to rapid recovery of soil structural conditions, including reductions in bulk density and penetration resistance, and enhanced infiltration, resulting in yield increases of 6% for maize and 26% for soybean. Consistent with these findings, the largely neutral yield response observed under RT+RR (Figure 7a) coincided with near-neutral changes in soil conditions under this practice.

4.2.2. Effects of soil hydraulic properties

Changes in saturated hydraulic conductivity were positively correlated with yield responses (Figure 7a) ($r = 0.79$), highlighting the critical role of macropore-mediated flow in regulating key soil hydrological processes such as infiltration. The influence of near-saturated hydraulic conductivity on yield variability was not explicitly analysed because of insufficient data and therefore warrants further investigation. Nevertheless, the influence of K_h is expected be substantial given its importance for soil water redistribution and drainage (Blanchy et al., 2023a; Bonetti et al., 2021), processes that directly affect crop yield. Consequently, the observed substantial reductions in K_h under NT, which is also inline with findings Blanchy et al. (2023a),



may limit effective replenishment of soil moisture, redistribution of water within the soil profile and subsequent plant water uptake, as well as drainage of excess water below the root zone (Wankmüller et al., 2024). Consistent with our finding, a global meta-analysis by Mondal and Chakraborty (2022) reported an overall reduction (70%, $p < 0.05$) in soil hydraulic conductivity in tropical soils under NT, where precipitation events are most intense and a large hydraulic conductivity is essential to enable infiltration, replenish the soil water storage, and prevent surface runoff with erosion. Moreover, high hydraulic conductivity is most critical to facilitate internal soil drainage, thereby reducing the risk waterlogging in clayey soils – one of the main yield-reducing conditions in such regions (Wakjira et al., 2026). These mechanisms are reflected in our dataset, where overall declines in soil hydraulic conductivity in clayey soils and humid climates under NT (Figure 3a, b) coincided with substantial yield penalties (Figure 5a, b).

The sensitivity of yield to changes in available water capacity and wilting point under NT (Figure 6a) reflects the critical role of tillage to maintain soil pore distribution for optimal soil water storage, availability to roots and soil aeration, especially when adoption of CA as a full package is not possible. Under NT, concurrent increases in water retention at both field capacity and wilting point across soil types (Figure 4) alter the balance between plant-available and plant-unavailable water. In particular, increases in wilting point expand the fraction of plant-unavailable water, thereby reducing effective water availability. In our datasets, changes in wilting point were negatively correlated with changes in yield ($r = -0.38$) (Figure 7b), indicating that increases in plant-unavailable water capacity can exacerbate water stress and lead to earlier onset of wilting as the soil dries (Wankmüller et al., 2024). Changes in air-capacity -- a key soil hydraulic parameter, particularly in wet climate and poorly drained soils -- were positively correlated with changes in yield ($r = 0.39$), implying that the reductions in aeration pores observed, particularly under no-till (Figure 2a), may contribute to yield penalties, particularly in humid and irrigated areas with clayey soils.

4.3. Effects of CA practices by climatic, soil type and practice duration

4.3.1. Effects of climate

Robust climate-specific effects of CA practices on crop yields emerge when NT is adopted alone. Our analysis, based on 49 observations from 29 studies, showed that NT without residue retention has robust positive effects (+16.3%) on yields in semi-dry climates (Figure 8a). By contrast, the only existing global meta-analysis to our knowledge that explicitly assessed NT alone in dry climates, based on 91 observations from 17 studies (Pittelkow et al., 2015a), reported a robust negative effects (-11.9%) of NT alone on rainfed crop yields in dry climates ($AI < 0.65$ as classified in the study). However, when effects are analysed irrespective of residue retention for semi-dry conditions, NT has a neutral effect on overall yields in our dataset (Supplementary Table 2), consistent with previous findings for overall crops (Cui et al., 2024; Pittelkow et al., 2015b; Sun et al., 2024). The observed yield gains under NT without residue in semi-dry climates is likely attributable to a combination of robust positive effects on hydraulic conductivity and improved moisture availability resulting from weak but favourable



changes in infiltration and available water capacity, together with weak negative effects of limiting factors such as increases in wilting point and penetration resistance (Figure 8a). Li et al. (2020), based on analysis of a comparable number of observations, similarly reported increases in available water capacity, but contrastingly larger increases in penetration resistance and hydraulic conductivity under NT in regions with annual rainfall <600mm.

550

In contrast, NT without residue retention was associated with robust negative effects on yield in humid and dry climates (Figure 8a). These patterns are consistent with the synthesis of Pittelkow et al. (2015a, b), who reported yield reductions of 5.7% for irrigated crops in dry regions ($AI < 0.65$), 7.6% for rainfed crops in humid areas, and 9.2% for irrigated crops in humid areas. These yield penalties coincided with adverse changes in key soil properties, particularly hydraulic conductivity, which governs
555 soil drainage, air-capacity which ensures soil aeration and reduced waterlogging risks under excess moisture, and penetration resistance which constrains root growth. The compaction-driven deterioration of soil conditions under NT in humid regions likely results from the use of heavy machinery on soils that are too wet to resist compaction. Farmers in humid regions often have greater access to mechanization and must complete field operations within relatively narrow windows of suitable soil moisture conditions for trafficability. In addition, soils in many humid regions are dominated by non-expansive kaolinite clay
560 minerals (Ito and Wagai, 2017), for which natural recovery from compaction is slow (Keller et al., 2025). As a result, increased risks of waterlogging, poor seed emergence, and related constraints can ultimately reduce crop yield.

Pittelkow et al. (2015a) further concluded, based on 213 observations from 34 studies, that NT with residue retention and crop rotation performs comparably to conventional practice (-3.0% , $p > 0.05$) in dry climates under non-limiting water conditions.
565 Our dataset (213 observations; 79 studies) analysed for NT with residue retention, regardless of crop rotation in similar climates ($AI < 0.65$), showed a similar outcome (-3.96% , $p > 0.05$). When restricting the analysis to extremely dry regions ($AI < 0.3$) across all practices evaluated, we found that such climates are the least suitable for adoption of both NT and RT, irrespective of residue retention or removal (Figure 8a). This is possibly due to soil structural degradation due to rapid wetting-drying cycles between irrigation events in dry climates, particularly when irrigation frequency is low (Yang et al., 2025). In addition,
570 soil slaking problems may be more pronounced in irrigated soils under dry climates due to relatively low soil organic carbon (SOC). For example, Jones et al. (2021) reported that extreme slaking occurred in soils with organic carbon contents below 1.1% in southwest Australia. In our dataset, approximately 29% of SOC observations (under no-till) in dry climates fall below this threshold, compared with 22% in semi-dry climates and 17% in humid climates. Furthermore, soil salinity is relatively high in drylands (Wang et al., 2025), and irrigated soils in these regions may therefore be prone to salinity-induced deterioration
575 of soil structure. However, whether no-till systems aggravate or alleviate problems such as slaking and salinity-related structural degradation in these environments remains unclear and warrants further investigation. In semi-dry climates, effects on yield are neutral under both NT and RT when combined with residue retention.

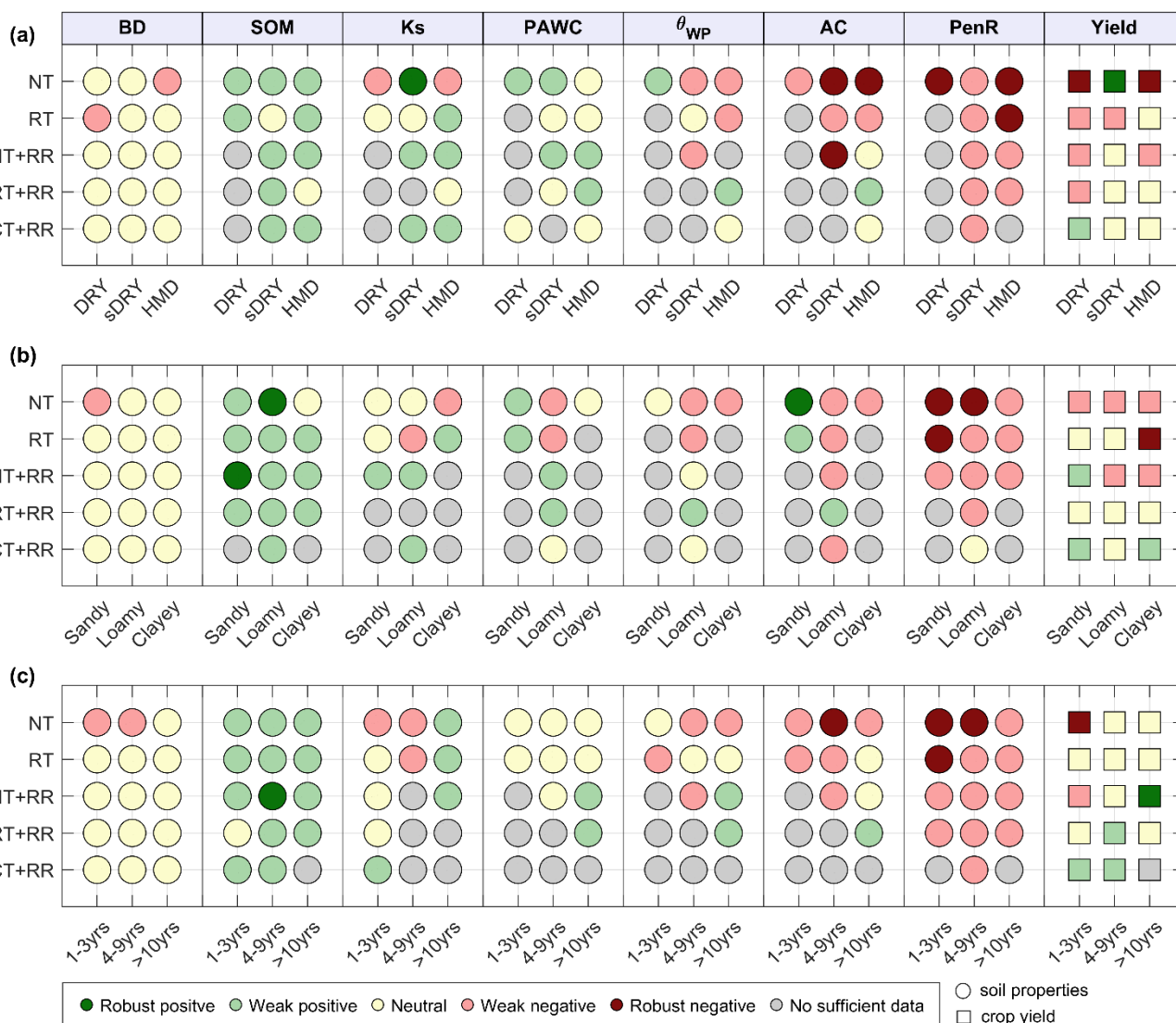


Figure 8: Changes in soil properties and crop yield under conservation tillage and residue retention in different climate, soil texture, and over practice duration. a) Effects of no-till (NT) and reduced tillage (RT), with and without residue retention (RR), on soil properties governing soil-plant-water relationships: bulk density (BD), soil organic matter (SOM), saturated hydraulic conductivity (K_s), available water capacity (PAWC), water retention at wilting point (θ_{WP}), air-capacity (AC), penetration resistance (PenR), and crop yield in dry (aridity index, $AI < 0.3$), semi-dry (sDRY; $0.3 < AI \leq 0.65$) and humid (HMD; $AI > 0.65$) climates. Effects were classified as robust when statistically significant ($p < 0.05$), weak when not significant but with an absolute effect size $> 5\%$, and neutral otherwise. Effects were interpreted in relative to their implication for yield, i.e., the effect is considered positive if it favours crop yield and vice versa. To account for this, the sign of the effects on PenR was reversed, since higher PenR generally reduces yield. **b)** Same analysis as in (a), but data were grouped by soil texture: sandy (sand, sandy loam, loamy sand, and sandy clay loam), loamy (loam, silty loam, clay loam, silty clay loam, and silt), and clayey (sandy clay, clay and silty clay). **c)** Same analysis as in (a) and (b), focusing on the duration of the conservation practices: 1-3 years, 4-9 years, and >10 years.



4.3.2. Effects of soil texture

The productivity limits of NT, irrespective of residue retention (weak negative), are also evident across soil types, with weak negative yield responses except in sandy soils under NT+RR (Figure 8b). Under NT without residue, the effects are consistent with weak but adverse changes in soil hydraulic properties, particularly hydraulic conductivity and wilting point, two of the major drivers of yield variability (Figure 6a), as well as penetration resistance. In sandy soils, all CA practices evaluated, except NT without residue retention, resulted in neutral or weakly positive yield responses, making sandy soil the most favourable soil category for CA adoption. This probably reflects compaction-induced beneficial redistribution of soil pores (Figure 8b), including increases in available water capacity, which is inherently low in sandy soils (see Figure 4), and reductions in air-filled macropores, which are instead inherently high, thereby improving water retention and contributing positively to yield. In loamy soils, yields were largely neutral across CA practices, except under NT with and without residue retention. In clayey soils, yields could be maintained or improved only under RT+RR and CT+RR. These patterns are consistent with previous meta-analyses reporting yield gains in sandy soils and yield penalties in clayey soils. For example, Achankeng and Cornelis, (2023) reported yield penalties under NT and RT, irrespective of residue management, for maize and spring cereals in Europe. Similarly, Shakoor et al. (2021) and Zhang et al. (2022) reported global yield penalties under NT regardless of residue management. Despite limited data to fully resolve the mechanisms driving yield responses under NT and RT combined with residue retention, the predominantly neutral to positive yield effects observed here are consistent with concurrent positive changes in soil organic matter (Figure 8b).

4.3.3. Practice duration effects

There is established evidence that, although CA practices can offer agronomic benefits in some cases also shortly after adoption, they are often associated with yield penalties in the initial years, with yields typically maintained, or in some cases even increased, over the longer term (Corbeels et al., 2020; Giller et al., 2009; Pittelkow et al., 2015a). Our analysis confirms this: during the first three years following adoption, robust negative effects under NT, and weak negative effects under NT+RR and RT were observed (Figure 8c). These short-term yield penalties are consistent with predominantly adverse (and occasionally neutral) changes in soil hydraulic properties and increased mechanical resistance. In the mid-term (4–9 years) and long term (≥ 10 years), yields were generally maintained rather than enhanced, except for NT+RR after 10 years, where robust positive yield responses were observed. This longer-term benefit coincided with weak but favourable changes in soil organic matter and hydraulic properties, together with weak decreases in penetration resistance. Notably, our analysis also indicates that yields are maintained during the first three years under RT+RR (Figure 8c).



4.4. Limitations of this study

We acknowledge that crop rotation -- the third pillar of CA -- was not included in this study. Alternating rooting systems introduced under crop rotation, depending on the crop species being rotated, can improve soil hydraulic and mechanical properties (Dimattia et al., 2025), thereby enhancing beneficial soil-plant-water relationships, in addition to its other benefits for soil biodiversity, nutrient cycling, and greenhouse gas emission reductions (Yang et al., 2024). Future work should assess the contexts in which crop rotation can meaningfully contribute to maintaining or enhancing soil-plant-water relationships under reduced soil disturbance, considering key factors such as soil type, climate, and crop combinations.

Regional differences in the extent of compaction-induced changes in soil properties, relative to the predominant causes of compaction, were not explicitly considered in this analysis. The severity of compaction problems, and the cascading effects on soil hydraulic properties and crop yields, can vary among regions depending on the predominant drivers, including use of heavy machinery, low soil organic matter content, compaction by livestock during grazing, and rapid wetting-drying cycles (Hamza and Anderson, 2005). In regions where heavy agricultural machinery is widely employed, compaction risks are particularly severe (Keller et al., 2025). Effects on yields can, however, vary regionally too, driven in part by differences in nutrient inputs: yield penalties may be reduced to some extent in high-input systems, whereas negative effects can be more pronounced in low-input systems where nutrient input including residue retention is limited (Corbeels et al., 2020; Pittelkow et al., 2015b).

To reduce complexity, our analysis averages responses across crop types. However, cereals account for 84% of the dataset, with maize and wheat alone representing 50% (Figure 1c). Crop-specific responses are nevertheless important, as changes in soil properties and yield can vary among crop types. For example, Pittelkow et al. (2015b), reported the largest yield penalties under NT for root crops, followed by cereals and legumes, whereas oilseed yields were largely maintained. As with other meta-analyses, our results are subject to uncertainties from multiple sources, including limited sample sizes for some practice contexts. To ensure sufficient observations for each analysis, moderators such as climate, soil type, and practice duration were categorised, which may mask variability within categories.

5. Conclusions

Transition from conventional to conservation agricultural practices is accompanied by some degree of modifications to soil properties that regulate soil-plant-water relationships and ultimately affect crop yield. Our analysis reinforces existing evidence that yield benefits and trade-offs depend on whether the conservation agricultural practices are adopted as a package or only partially. Globally, yield penalties are generally greatest when no-till is adopted alone and decrease with increasing tillage intensity and residue retention. The drivers of yield penalty under no-till are primarily compaction-induced changes in soil properties, specifically: (i) reduced near-saturated soil hydraulic conductivity, which constrains key processes such as soil



moisture redistribution and availability to plant roots, as well as drainage of excess water from of the root zone; (ii) increased dense soil matrix, which disconnects macropores – the pathways through which roots preferentially grow through – thereby limiting root elongation and access to water and nutrients; and (iii) increased fine soil pore fraction that raises plant-unavailable soil water fractions (i.e., higher moisture content at wilting point), potentially increasing the risk of water stress for crops. When reduced soil disturbance and residue retention are combined (as in reduced tillage with residue retention under which the overall yield penalty was minimal), increases in soil organic matter and saturated hydraulic conductivity are, instead, the dominant drivers of yield variability (rather than water retention parameters).

660

However, benefits and trade-offs are context dependent, underscoring the importance of tailored adoption of CA practices. We conclude that no-till can increase yields in semi-dry climate, although benefits can be limited during the first three years following adoption. In contrast, no-till alone is unsuitable in dry and humid climates, where compaction-induced constraints related to poor soil drainage, limited soil aeration, and restricted root growth lead to yield penalties. In dry climates where irrigation is dominant, it appears necessary to till to alleviate compaction arising from rapid wetting-drying cycles, which otherwise would exacerbate yield penalties. Yield responses are further modulated by soil texture: owing to their lower susceptibility to structural degradation under compaction, sandy soils generally maintain or improve yields under all CA practices evaluated, except under NT without residue retention. Conversely, in clay-dominated soils, which are highly prone to structural degradation, at least minimum tillage combined with residue retention is required to maintain yields.

670 **Author contributions**

Conceptualization: MTW, with input from RH, JvH, JS, and KD. Methodology: MTW, RH, JvH, JK, SB, JS, and KD. Data collection: MTW. Formal analysis: MTW, with input from RH and JvH. Interpretation of results and validation: MTW, RH, JvH, JK, SB, JS and KD. Original draft preparation: MTW. Review and editing: RH, JvH, SB, JK, JS, and KD. Supervision: KD.

675 **Competing interests**

The authors declare that none of the authors has any competing interests.

Code and data availability

Codes and datasets used in this study (Wakjira, 2026) are available at <https://doi.org/10.5281/zenodo.20200561>.



Acknowledgements

680 We thank Ken Giller for his constructive comments and valuable discussions on this work. We are also grateful to the authors of all studies included in this analysis for making their experimental data and analyses publicly available. Due to the large number of studies included in this analysis, it was not possible to cite all original source papers individually.

Financial support

This research was supported by the Swiss National Science Foundation (SNSF; Postdoc.Mobility grant number PN_222299, 685 granted to Mosisa Tujuba Wakjira). Sara Bonetti acknowledges funding from the Swiss National Science Foundation (SNSF, Grant number 10000638)

References

- Achankeng, E. and Cornelis, W.: Conservation tillage effects on European crop yields: A meta-analysis, *F. Crop. Res.*, 298, 108967, <https://doi.org/10.1016/j.fcr.2023.108967>, 2023.
- 690 Adams, D. C., Gurevitch, J., and Rosenberg, M. S.: Resampling tests for meta-analysis of ecological data, 78, 1277–1283, 1997.
- Amrhein, V., Greenland, S., and McShane, B.: Retire statistical significance, *Nature*, 567, 305–307, <https://doi.org/10.1038/d41586-019-00857-9>, 2019.
- Andersson, J. A. and D’Souza, S.: From adoption claims to understanding farmers and contexts: A literature review of 695 Conservation Agriculture (CA) adoption among smallholder farmers in southern Africa, *Agric. Ecosyst. Environ.*, 187, 116–132, <https://doi.org/10.1016/j.agee.2013.08.008>, 2014.
- Araya, T., Ochsner, T. E., Mkeni, P. N. S., Hounkpatin, K. O. L., and Amelung, W.: Challenges and constraints of conservation agriculture adoption in smallholder farms in sub-Saharan Africa: A review, *Int. Soil Water Conserv. Res.*, 12, 828–843, <https://doi.org/10.1016/j.iswcr.2024.03.001>, 2024.
- 700 Aschi, F., Dekker, S. C., Leclère, D., Marques, A., Neumann, C., Ambrosio, G., and van Vuuren, D. P.: Can we bend the curve: Trends in global biodiversity scenarios, *Sci. Adv.*, 12, eaeb2277, <https://doi.org/10.1126/sciadv.aeb2277>, 2026.
- Bengough, A. G., McKenzie, B. M., Hallett, P. D., and Valentine, T. A.: Root elongation, water stress, and mechanical impedance: A review of limiting stresses and beneficial root tip traits, *J. Exp. Bot.*, 62, 59–68, <https://doi.org/10.1093/jxb/erq350>, 2011.
- 705 Blake, G. R. and Hartge, K. H.: Bulk density, in: *Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods*, edited by: Klute, A., Soil Science Society of America, Madison, WI, 363–375, <https://doi.org/10.2136/sssabookser5.1.2ed.c13>, 1986.
- Blanchy, G., Albrecht, L., Bragato, G., Garré, S., Jarvis, N., and Koestel, J.: Impacts of soil management and climate on saturated and near-saturated hydraulic conductivity : analyses of the Open Tension-disk Infiltrometer Meta-database (OTIM),



HESS, 2703–2724, 2023a.

- 710 Blanchy, G., Bragato, G., Di Bene, C., Jarvis, N., Larsbo, M., Meurer, K., and Garré, S.: Soil and crop management practices and the water regulation functions of soils: a qualitative synthesis of meta-analyses relevant to European agriculture, *SOIL*, 9, 1–20, <https://doi.org/10.5194/soil-9-1-2023>, 2023b.
- Bonetti, S., Wei, Z., and Or, D.: A framework for quantifying hydrologic effects of soil structure across scales, *Commun. Earth Environ.*, 2, <https://doi.org/10.1038/s43247-021-00180-0>, 2021.
- 715 Borenstein, M., Hedges, L. V., Higgins, J. P. T., and Rothstein, H. R.: A basic introduction to fixed-effect and random-effects models for meta-analysis, *Res. Synth. Methods*, 1, 97–111, <https://doi.org/10.1002/jrsm.12>, 2010.
- Brouder, S. M. and Gomez-Macpherson, H.: The impact of conservation agriculture on smallholder agricultural yields: A scoping review of the evidence, *Agric. Ecosyst. Environ.*, 187, 11–32, <https://doi.org/10.1016/j.agee.2013.08.010>, 2014.
- Ceriani, R., Fohrafellner, J., Maenhout, P., Jarosch, K. A., Weiss, L., Bene, C. Di, Baratella, V., Carboni, G., Mereu, V.,
720 Stefanova, M., Fava, F., and Valkama, E.: Cereal yield, yield stability, and nitrous oxide release in European conservation agriculture: A meta-analysis, *F. Crop. Res.*, 341, 110386, <https://doi.org/10.1016/j.fcr.2026.110386>, 2026.
- Colombi, T., Torres, L. C., Walter, A., and Keller, T.: Feedbacks between soil penetration resistance, root architecture and water uptake limit water accessibility and crop growth – A vicious circle, *Sci. Total Environ.*, 626, 1026–1035, <https://doi.org/10.1016/j.scitotenv.2018.01.129>, 2018.
- 725 Corbeels, M., Naudin, K., Whitbread, A. M., Kühne, R., and Letourmy, P.: Limits of conservation agriculture to overcome low crop yields in sub-Saharan Africa, *Nat. Food*, 1, 447–454, <https://doi.org/10.1038/s43016-020-0114-x>, 2020.
- Cui, Y., Zhang, W., Zhang, Y., Liu, X., Zhang, Y., Zheng, X., Luo, J., and Zou, J.: Effects of no-till on upland crop yield and soil organic carbon: a global meta-analysis, *Plant Soil*, 499, 363–377, <https://doi.org/10.1007/s11104-022-05854-y>, 2024.
- Descheemaeker, K., Ronner, E., Ollenburger, M., Franke, A. C., Klapwijk, C. J., Falconnier, G. N., Wichern, J., and Giller, K.
730 E.: WHICH OPTIONS FIT BEST? OPERATIONALIZING the SOCIO-ECOLOGICAL NICHE CONCEPT, *Exp. Agric.*, 55, 169–190, <https://doi.org/10.1017/S001447971600048X>, 2019.
- Dimattia, B. G., Righi, A., Bettuzzi, M., Koestel, J., Morigi, M. P., Brancaccio, R., Salvi, S., Hernandez-Soriano, M. C., and Bittelli, M.: Root traits of different wheat cultivars influence soil structure: an X-ray computed tomography and root morphology study, *Geoderma*, 459, 117349, <https://doi.org/10.1016/j.geoderma.2025.117349>, 2025.
- 735 FAO: Conservation Agriculture, 1–2 pp., 2022.
- Feifel, M., Coucheney, E., Holzkämper, A., Heller, O., Wittwer, R., and Jarvis, N.: Term Effects of No- - Till Systems on Soil Structure and Function Under Climate Change : An Exploratory Modelling Study, <https://doi.org/10.1111/ejss.70259>, 2025.
- Giller, K. E.: Nitrogen fixation in tropical cropping systems, CABI, 442 pp., <https://doi.org/10.1079/9780851994178.0000>, 2001.
- 740 Giller, K. E., Witter, E., Corbeels, M., and Tittonell, P.: Conservation agriculture and smallholder farming in Africa: The heretics’ view, <https://doi.org/10.1016/j.fcr.2009.06.017>, 1 October 2009.
- Giller, K. E., Corbeels, M., Nyamangara, J., Triomphe, B., Affholder, F., Scopel, E., and Tittonell, P.: A research agenda to



- explore the role of conservation agriculture in African smallholder farming systems, *F. Crop. Res.*, 124, 468–472, <https://doi.org/10.1016/j.fcr.2011.04.010>, 2011.
- 745 Grömping, U.: Relative importance for linear regression in R: The package relaimpo, *J. Stat. Softw.*, 17, 1–27, <https://doi.org/10.18637/jss.v017.i01>, 2006.
- Hamza, M. A. and Anderson, W. K.: Soil compaction in cropping systems: A review of the nature, causes and possible solutions, *Soil Tillage Res.*, 82, 121–145, <https://doi.org/10.1016/j.still.2004.08.009>, 2005.
- Hartmann, M. and Six, J.: Soil structure and microbiome functions in agroecosystems, *Nat. Rev. Earth Environ.*, 4, 4–18, <https://doi.org/10.1038/s43017-022-00366-w>, 2023.
- 750 Haruna, S. I., Anderson, S. H., Nkongolo, N. V., and Zaibon, S.: Soil Hydraulic Properties: Influence of Tillage and Cover Crops, *PEDOSPHERE*, 28, 430–442, [https://doi.org/10.1016/S1002-0160\(17\)60387-4](https://doi.org/10.1016/S1002-0160(17)60387-4), 2018.
- Hatfield, J. L., Sauer, T. J., Prueger, J. H., Hatfield, J. L., Sauer, T. J., and Prueger, J. H.: Hatfield, Sauer, Prueger - 2001 - Managing soils to achieve greater water use efficiency A review, 2001.
- 755 Heller, O., Di Bene, C., Nino, P., Huyghebaert, B., Arlauskienė, A., Castanheira, N. L., Higgins, S., Horel, A., Kir, A., Kizeková, M., Lacoste, M., Munkholm, L. J., O’Sullivan, L., Radzikowski, P., Rodríguez-Cruz, M. S., Sandén, T., Šarūnaitė, L., Seidel, F., Spiegel, H., Stalenga, J., Uusi-Kämpä, J., Vervuurt, W., Keller, T., and Vanwindekens, F.: Towards enhanced adoption of soil-improving management practices in Europe, *Eur. J. Soil Sci.*, 75, 1–17, <https://doi.org/10.1111/ejss.13483>, 2024.
- 760 Hillel, D.: *Environmental Soil Physics*, Toronto, 801 pp., 1998.
- Hobbs, P. R., Sayre, K., and Gupta, R.: The role of conservation agriculture in sustainable agriculture, 543–555, <https://doi.org/10.1098/rstb.2007.2169>, 2008.
- Ito, A. and Wagai, R.: Data Descriptor: Global distribution of clay-size minerals on land surface for biogeochemical and climatological studies, *Sci. Data*, 4, 1–11, <https://doi.org/10.1038/sdata.2017.1031>, 2017.
- 765 Jarvis, N. J.: A review of non-equilibrium water flow and solute transport in soil macropores: Principles, controlling factors and consequences for water quality, *Eur. J. Soil Sci.*, 58, 523–546, <https://doi.org/10.1111/j.1365-2389.2007.00915.x>, 2007.
- Jones, E. J., Filippi, P., Wittig, R., Fajardo, M., Pino, V., and Mcbratney, A. B.: Mapping soil slaking index and assessing the impact of management in a mixed agricultural landscape, *Soil*, 7, 33–46, <https://doi.org/10.5194/soil-7-33-2021>, 2021.
- Kassam, A., Friedrich, T., Shaxson, F., and Pretty, J.: The spread of Conservation Agriculture : Justification , sustainability and uptake 1, 2008, 292–320, <https://doi.org/10.3763/ijas.2009.0477>, 2009.
- 770 Keller, T., Bickel, S., and Or, D.: The invisible subsoil compaction risk under no- till farming, *Proc. Natl. Acad. Sci.*, 122, <https://doi.org/10.1073/pnas>, 2025.
- Kreiselmeier, J., Chandrasekhar, P., Weninger, T., Schwen, A., Julich, S., Feger, K. H., and Schwärzel, K.: Temporal variations of the hydraulic conductivity characteristic under conventional and conservation tillage, *Geoderma*, 362, <https://doi.org/10.1016/j.geoderma.2019.114127>, 2020.
- 775 Kuhlmann, A., Neuweiler, I., Van Der Zee, S. E. A. T. M., and Helmig, R.: Influence of soil structure and root water uptake



- strategy on unsaturated flow in heterogeneous media, *Water Resour. Res.*, 48, 1–16, <https://doi.org/10.1029/2011WR010651>, 2012.
- Lal, R.: A system approach to conservation agriculture, *J. Soil Water Conserv.*, 70, 82A–88A, <https://doi.org/10.2489/jswc.70.4.82A>, 2015.
- Li, Y., Li, Z., Cui, S., and Zhang, Q.: Geoderma Trade-off between soil pH, bulk density and other soil physical properties under global no-tillage agriculture, *Geoderma*, 361, 114099, <https://doi.org/10.1016/j.geoderma.2019.114099>, 2020.
- Lohmann, P. M., Pizzo, A., Bauer, J. M., Khanna, T. M., Flecke, S. L., Callaghan, M., Minx, J. C., and Reisch, L. A.: A meta-analysis assessing the effectiveness of demand-side interventions for sustainable food consumption and food waste reduction, *Nat. Food*, 7, <https://doi.org/10.1038/s43016-025-01279-9>, 2026.
- Mondal, S. and Chakraborty, D.: Global meta-analysis suggests that no-tillage favourably changes soil structure and porosity, *Geoderma*, 405, <https://doi.org/10.1016/j.geoderma.2021.115443>, 2022.
- Muff, S., Nilsen, E. B., O'Hara, R. B., and Nater, C. R.: Rewriting results sections in the language of evidence, *Trends Ecol. Evol.*, 37, 203–210, <https://doi.org/10.1016/j.tree.2021.10.009>, 2022.
- Peixoto, D. S., Silva, B. M., de Oliveira, G. C., Moreira, S. G., da Silva, F., and Curi, N.: A soil compaction diagnosis method for occasional tillage recommendation under continuous no tillage system in Brazil, *Soil Tillage Res.*, 194, 104307, <https://doi.org/10.1016/j.still.2019.104307>, 2019a.
- Peixoto, D. S., Silva, B. M., de Oliveira, G. C., Moreira, S. G., da Silva, F., and Curi, N.: A soil compaction diagnosis method for occasional tillage recommendation under continuous no tillage system in Brazil, *SOIL TILLAGE Res.*, 194, <https://doi.org/10.1016/j.still.2019.104307>, 2019b.
- Peralta, G., Alvarez, C. R., and Taboada, M. A.: Soil compaction alleviation by deep non-inversion tillage and crop yield responses in no tilled soils of the Pampas region of Argentina. A meta-analysis, *SOIL TILLAGE Res.*, 211, <https://doi.org/10.1016/j.still.2021.105022>, 2021.
- Pittelkow, C. M., Liang, X., Linquist, B. A., Van Groenigen, L. J., Lee, J., Lundy, M. E., Van Gestel, N., Six, J., Venterea, R. T., and Van Kessel, C.: Productivity limits and potentials of the principles of conservation agriculture, *Nature*, 517, 365–368, <https://doi.org/10.1038/nature13809>, 2015a.
- Pittelkow, C. M., Linquist, B. A., Lundy, M. E., Liang, X., van Groenigen, K. J., Lee, J., van Gestel, N., Six, J., Venterea, R. T., and van Kessel, C.: When does no-till yield more? A global meta-analysis, *F. Crop. Res.*, 183, 156–168, <https://doi.org/10.1016/j.fcr.2015.07.020>, 2015b.
- Poggio, L., De Sousa, L. M., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Ribeiro, E., and Rossiter, D.: SoilGrids 2.0: Producing soil information for the globe with quantified spatial uncertainty, *Soil*, 7, 217–240, <https://doi.org/10.5194/soil-7-217-2021>, 2021.
- Pretty, J.: Intensification for redesigned and sustainable agricultural systems, *Science* (80-.), 362, <https://doi.org/10.1126/science.aav0294>, 2018.
- Pretty, J. and Bharucha, Z. P.: Sustainable intensification in agricultural systems, *Ann. Bot.*, 114, 1571–1596,



- <https://doi.org/10.1093/aob/mcu205>, 2014.
- Van den Putte, A., Govers, G., Diels, J., Gillijns, K., and Demuzere, M.: Assessing the effect of soil tillage on crop growth: A meta-regression analysis on European crop yields under conservation agriculture, *Eur. J. Agron.*, 33, 231–241, <https://doi.org/10.1016/j.eja.2010.05.008>, 2010.
- 815 Rabot, E., Wiesmeier, M., Schlüter, S., and Vogel, H. J.: Soil structure as an indicator of soil functions: A review, *Geoderma*, 314, 122–137, <https://doi.org/10.1016/j.geoderma.2017.11.009>, 2018.
- Ranaivoson, L., Naudin, K., Ripoche, A., Affholder, F., Rabearisoa, L., and Corbeels, M.: Agro-ecological functions of crop residues under conservation agriculture. A review, *Agron. Sustain. Dev.*, 37, <https://doi.org/10.1007/s13593-017-0432-z>, 2017.
- 820 Reichert, J. M., Suzuki, L. E. A. S., Reinert, D. J., Horn, R., and Håkansson, I.: Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils, *Soil Tillage Res.*, 102, 242–254, <https://doi.org/10.1016/j.still.2008.07.002>, 2009.
- Rodenburg, J., Büchi, L., and Hagggar, J.: Adoption by adaptation: moving from Conservation Agriculture to conservation practices, *Int. J. Agric. Sustain.*, 5903, 1–19, <https://doi.org/10.1080/14735903.2020.1785734>, 2020.
- 825 Saltelli, A. and Ratto, M.: *Global Sensitivity Analysis. The Primer*. John Wiley & Sons, Ltd, Chichester, UK., John Wiley & Sons, Ltd, Chichester, UK. pp., 2008.
- van de Schoot, R., Bruin, J. De, Schram, R., Zahedi, P., Boer, J. De, Weijdem, F., Kramer, B., Huijts, M., Hoogerwerf, M., Ferdinands, G., Harkema, A., Willemsen, J., Ma, Y., Fang, Q., Hindriks, S., Tummers, L., and Oberski, D. L.: efficient and transparent systematic reviews, *Nat. Mach. Intell.*, 3, 125–133, <https://doi.org/10.1038/s42256-020-00287-7>, 2021.
- 830 Shakoob, A., Shahbaz, M., Farooq, T. H., Sahar, N. E., Shahzad, S. M., Altaf, M. M., and Ashraf, M.: A global meta-analysis of greenhouse gases emission and crop yield under no-tillage as compared to conventional tillage, *Sci. Total Environ.*, 750, 142299, <https://doi.org/10.1016/j.scitotenv.2020.142299>, 2021.
- Six, J., Feller, C., Denef, K., Ogle, S., Joao Carlos, de M. S., and Albrecht, A.: Soil organic matter, biota and aggregation in temperate and tropical soils - Effects of no-tillage, *Agronomie*, 22, 755–775, <https://doi.org/10.1051/agro:2002043>, 2002.
- 835 Sterne, J. A. C. and Egger, M.: Funnel plots for detecting bias in meta-analysis: Guidelines on choice of axis, *J. Clin. Epidemiol.*, 54, 1046–1055, [https://doi.org/10.1016/S0895-4356\(01\)00377-8](https://doi.org/10.1016/S0895-4356(01)00377-8), 2001.
- Sun, J., Niu, W. Q., Du, Y. D., Ma, L., Huang, S. Y., Mu, F., Zhang, Q., Li, G. C., Zhu, J. J., and Siddique, K. H. M.: Regionally adapted conservation tillage reduces the risk of crop yield losses: A global meta-analysis, *SOIL TILLAGE Res.*, 244, <https://doi.org/10.1016/j.still.2024.106265>, 2024.
- 840 Suzuki, L., Reichert, J. M., and Reinert, D. J.: Degree of compactness, soil physical properties and yield of soybean in six soils under no-tillage, *SOIL Res.*, 51, 311–321, <https://doi.org/10.1071/SR12306>, 2013.
- Viechtbauer, W.: *Journal of Statistical Software*, 36, 2010.
- Wade, T., Claassen, R., and Wallander, S.: Conservation-Practice Adoption Rates Vary Widely by Crop and Region, *EIB-147*, 1–34 pp., 2015.



- 845 Wakjira, M. T.: Global dataset of soil properties and crop yield responses under conservation agriculture from 361
experimental sites, <https://doi.org/10.5281/zenodo.20200561>, May 2026.
- Wakjira, M. T., Molnar, P., Bartholomeus, R., Erkossa, T., and Descheemaeker, K.: Agrohydrological analysis of waterlogging
impacts and mitigation in Ethiopia, In review, 1–33, <https://doi.org/10.21203/rs.3.rs-7982727/v1>, 2026.
- Walkley, A. and Black, I. A.: An examination of the Degtjareff method for determining soil organic matter, and a proposed
850 modification of the chromic acid titration method, *Soil Sci.*, 37, 29–38, <https://doi.org/10.1097/00010694-193401000-00003>,
1934.
- Wang, T., Dong, J., Lyu, B., Gao, X., Wang, N., and Shi, Z.: High-resolution global soil salinity and sodicity mapping (1980–
2024): Box-Cox-based sample optimization, multi-source remote sensing features, and uncertainty quantification, *Remote
Sens. Environ.*, 330, 114991, <https://doi.org/10.1016/j.rse.2025.114991>, 2025.
- 855 Wankmüller, F. J. P., Delval, L., Lehmann, P., Baur, M. J., Cecere, A., Wolf, S., Or, D., Javaux, M., and Carminati, A.: Global
influence of soil texture on ecosystem water limitation, *Nature*, 635, 631–638, <https://doi.org/10.1038/s41586-024-08089-2>,
2024.
- Widmer, A., Johannes, A., Fontana, M., Sommer, M., Elfouki, S., Bragazza, L., and Koestel, J.: Short-term impact of
mechanical loosening on physical soil properties in a severely compacted subsoil, *Geoderma*, 464, 117611,
860 <https://doi.org/10.1016/j.geoderma.2025.117611>, 2025.
- Wooster, E. I. F., Lundgre, E. J., Nimmo, D. G., Cowan, M. A., Fricke, E. C., Frank, A. S. K., Carthey, A. J. R., Grabowski,
K. L., Green, J. R., Linley, G. D., McEvoy, T. J., Simpson, A., Westaway, D., Wrensford, K. C., Wright, N. S., Nakagawa, S.,
and Gaynor, K. M.: Article in Press Predator-prey temporal niche partitioning under human disturbance : a meta-analysis TI
IN, *Nat. Commun.*, <https://doi.org/10.1038/s41467-026-69113-9>, 2026.
- 865 Wu, L., Pan, L., Mitchell, J., and Sanden, B.: Measuring Saturated Hydraulic Conductivity using a Generalized Solution for
Single-Ring Infiltrometers, 63, 891–895, <https://doi.org/10.2136/sssaj1999.634788x>, 1999.
- Xiao, L., Wang, Y., Zhang, C., Zhao, K., Zhao, R., and Xie, Z.: Crop rotation enhances yield and water productivity:
Uncovering potential drivers through global field experiment synthesis, *Agric. Water Manag.*, 317, 109644,
<https://doi.org/10.1016/j.agwat.2025.109644>, 2025.
- 870 Yang, F., Wu, P., Zhang, L., Hang, Y., and Wei, Y.: Effects of irrigation-mediated continuously moist and dry-rewetting
pattern on soil physicochemical properties, structure and bacterial community, *Appl. Soil Ecol.*, 205, 105767,
<https://doi.org/10.1016/j.apsoil.2024.105767>, 2025.
- Yang, P., Dong, W., Heinen, M., Qin, W., and Oenema, O.: Soil Compaction Prevention, Amelioration and Alleviation
Measures Are Effective in Mechanized and Smallholder Agriculture: A Meta-Analysis, *Land*, 11,
875 <https://doi.org/10.3390/land11050645>, 2022.
- Yang, X., Xiong, J., Du, T., Ju, X., Gan, Y., Li, S., Xia, L., Shen, Y., Pacenka, S., Steenhuis, T. S., Siddique, K. H. M., Kang,
S., and Butterbach-Bahl, K.: Diversifying crop rotation increases food production, reduces net greenhouse gas emissions and
improves soil health, *Nat. Commun.*, 15, <https://doi.org/10.1038/s41467-023-44464-9>, 2024.



- 880 Zhang, K., Li, Y., Wei, H., Zhang, L., Li, F. M., and Zhang, F.: Conservation tillage or plastic film mulching? A comprehensive
global meta-analysis based on maize yield and nitrogen use efficiency, *Sci. Total Environ.*, 831, 154869,
<https://doi.org/10.1016/j.scitotenv.2022.154869>, 2022.
- Zhao, J., Chen, J., Beillouin, D., Lambers, H., Yang, Y., Smith, P., Zeng, Z., Olesen, J. E., and Zang, H.: Global systematic
review with meta-analysis reveals yield advantage of legume-based rotations and its drivers, 1–9,
<https://doi.org/10.1038/s41467-022-32464-0>, 2022.
- 885 Zomer, R. J., Xu, J., and Trabucco, A.: Version 3 of the Global Aridity Index and Potential Evapotranspiration Database, *Sci.*
Data, 9, 1–15, <https://doi.org/10.1038/s41597-022-01493-1>, 2022.