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Effects of Conservation Agriculture on Soil Physical, Chemical and Biological Properties: A Review

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Abstract— *Conservation agriculture (CA), which rests on minimal soil disturbance, permanent soil cover and crop diversification, is widely promoted as a route to sustainable intensification, yet its effects on soil are neither uniform nor immediate. This review synthesises published evidence on how CA influences soil physical, chemical and biological properties, using soil organic carbon (SOC) as a unifying thread. Where climate and soil favour biomass production and management is well adapted, CA generally improves aggregate stability, infiltration, water storage and erosion control; it raises SOC and nutrient stocks, mainly in the topsoil; and it enhances microbial biomass, diversity, enzyme activity and macrofauna. Findings are far less consistent for bulk density, pH, cation exchange capacity and soil respiration. Nutrient stratification, compaction, surface sealing, waterlogging, cooler seedbeds and weed or disease pressure can offset the gains where residue production is poor, climates are cold and wet, or systems are not locally adapted. Benefits commonly take several years to appear. CA is therefore best understood as a flexible set of locally adapted practices rather than a fixed package. Priorities for future work include strategic tillage, locally suited rotations and fertiliser management, whole-profile and seasonal sampling, and standardised soil health indicators.*

Keywords— conservation agriculture, no-till, soil health, soil organic carbon, soil properties, sustainability.

I. INTRODUCTION

Agriculture faces a double challenge. Food production must rise to feed a population projected to grow from 7.7 billion in 2019 to 9.7 billion by 2050, yet this has to be achieved without eroding the ecosystem services that soils supply, including carbon storage, nutrient provision and regulation of the water cycle (Cárceles Rodríguez et al., 2022; Page et al., 2020). The scope for expanding cropland is limited, and existing farmland is increasingly threatened by degradation, water scarcity and a more variable climate (Page et al., 2020). Intensive conventional systems, which depend on repeated tillage, heavy machinery and high chemical inputs, are associated with greater compaction, erosion and salinisation and with losses of organic matter, nutrients and soil biodiversity, all of which weaken long-term productivity (Cárceles Rodríguez et al., 2022).

Conservation agriculture has been put forward as one of the main alternatives for sustainable intensification (Kassam et al., 2009; Lal, 2015). The Food and Agriculture Organization describes it through three linked principles: continuous minimum mechanical soil disturbance, permanent organic soil cover provided by residues or cover crops, and diversification of species through rotations, sequences and associations (Cárceles Rodríguez et al., 2022). Page et al. (2020) add a practical threshold, stating that at least 30% of the soil surface should remain covered between harvest and planting and that rotations should include legumes. The approach emerged in the United States in the 1930s as a response to wind and water erosion. By 2015/2016 it was practised on roughly 180 Mha, about 12.5% of global cropland (Kassam et al., 2019, as summarised by Cárceles Rodríguez et al., 2022), although uptake is concentrated on large farms in North America, Australia and Brazil, and smallholders account for only a small share of the area (Derpsch et al., 2010).

The benefits attributed to CA include greater soil water storage, reduced erosion, improved soil quality and, in some situations, higher yields and farm income (Page et al., 2020). Many of these benefits are linked to the build-up of soil organic matter, particularly at the soil surface, which supports aggregate stability, fertility and biological diversity (Page et al., 2020). Because soil health cannot be measured directly, it is assessed through indicators that span physical, chemical and biological properties, ideally organised as a minimum data set that responds to management and relates to soil function (Cárceles Rodríguez et al., 2022).

The picture is nonetheless complicated. Responses depend on climate, soil type, baseline SOC, the amount of residue produced, the length of time since conversion and the quality of local adaptation (Page et al., 2020; Cárceles Rodríguez et al., 2022). Bulk density, pH and cation exchange capacity, for example, have been reported to rise, fall or stay unchanged, and benefits can take three to seven years to emerge, with possible yield penalties or weed problems in the transition period (Stagnari et al., 2014). In cold, wet environments with poorly drained soils CA may not succeed at all (Page et al., 2020).

This review therefore examines how CA affects soil physical, chemical and biological properties, with SOC treated as the main link between them, and considers the conditions under which effects are positive, neutral or negative. It closes with the principal constraints on adoption and the research needs for locally adapted systems.

II. CONSERVATION AGRICULTURE: PRINCIPLES, ADOPTION AND TRANSITION

2.1 Principles and definitions

In its classical form CA combines three components applied together: minimal mechanical disturbance (no-till or very reduced tillage), permanent soil cover, and diversified cropping. Companion practices such as integrated nutrient and pest management are normally added on a site-specific basis (Lal, 2015; Thierfelder et al., 2018). Because many smallholders cannot implement all three components at once, several authors argue that the fixed three-part definition should give way to a broader notion of conservation practices that can be adopted separately or in stages (Giller et al., 2015; Rodenburg et al., 2020). Others propose a further principle, the appropriate use of fertiliser, especially in low-fertility sub-Saharan environments (Vanlauwe et al., 2014). This debate matters for interpreting the literature, since studies often test only no-till, or no-till with residue retention, rather than the complete system (Page et al., 2020).

2.2 Adoption

Global CA area grew by about 69% between 2008/2009 and 2015/2016 (Kassam et al., 2019, as summarised by Cárceles Rodríguez et al., 2022). Adoption by smallholders remains limited, owing partly to the complexity of the system, limited technical knowledge, scarce and unaffordable no-till seeding equipment, competing uses for residues and weak institutional support (Bhan and Behera, 2014; Andersson and D'Souza, 2014; Cárceles Rodríguez et al., 2022).

2.3 The transition period

Improvements in soil quality under CA are gradual. Stagnari et al. (2014) suggest that three to seven years may be required before the full benefits appear, which is why long-term trials are needed to detect real change. During the transition, farmers may face more difficult weed control and lower productivity (Farooq et al., 2011), and these early problems can lead to abandonment of the practice (Cárceles Rodríguez et al., 2022).

III. SOIL HEALTH AND ITS INDICATORS

The terms soil health and soil quality are often used interchangeably. A common distinction treats soil health as the broader capacity of soil to function as a living system supporting plants, animals and people (Laishram et al., 2012), and soil quality as the inherent capacity of a particular soil to deliver ecosystem services, whereas soil health reflects its actual present capacity (Bonfante et al., 2020). Definitions vary widely. Doran and Zeiss (2000) emphasise the capacity to function as a vital living system that sustains productivity and maintains water and air quality, while Kibblewhite et al. (2008) focus on a level of food and fibre production sufficient for human needs alongside continued delivery of other ecosystem services.

These definitions are conceptual. In practice soil health can only be inferred from measurable indicators that represent soil processes (Cárceles Rodríguez et al., 2022). No single indicator captures all functions, so a minimum data set that combines physical, chemical and biological measures is generally recommended (Bünemann et al., 2018; Lehmann et al., 2020). Typical physical indicators include aggregation, infiltration, penetration resistance, texture and water-holding capacity. Chemical indicators include organic carbon, pH, cation exchange capacity (CEC), electrical conductivity and available nutrients.

Biological indicators include microbial biomass and activity, respiration and nitrogen mineralisation (Cárceles Rodríguez et al., 2022). Good indicators are easy and inexpensive to measure, sensitive to management and informative for decisions, and their interpretation is always context-dependent (Fierer et al., 2021).

Individual indicators can be combined into composite indices that allow direct comparison among soils and support management decisions (Andrews et al., 2002). Such indices have drawbacks, however. Different construction methods can give different values for the same soil, and a single number can oversimplify the response of a complex agroecosystem (Cárceles Rodríguez et al., 2022). This review therefore treats the three groups of properties separately before bringing them together.

IV. EFFECTS OF CONSERVATION AGRICULTURE ON SOIL PHYSICAL PROPERTIES

Conventional tillage alters soil physical properties by degrading structure and promoting compaction, sealing and erosion. CA can reduce many of these effects, although the response depends on soil, climate and residue cover (Soane et al., 2012; Blanco-Canqui and Ruis, 2018).

4.1 Aggregate stability and soil structure

Soil structure governs water movement, biological habitat and resistance to erosion, and aggregate stability is the most widely used measure of structural condition (Bronick and Lal, 2005). Less disturbance, greater organic inputs and continuous plant cover all favour structural development. Several mechanisms operate together under CA. Surface residues shield aggregates from raindrop impact, decomposing organic matter promotes aggregation, and the absence of tillage allows fungal networks and root systems to persist and bind particles (Wang et al., 2010; Cárceles Rodríguez et al., 2022). Tillage, by contrast, breaks aggregates and exposes the organic matter they protect (Six et al., 2000).

A global meta-analysis found that water-stable aggregates were on average 31% more abundant under no-till than under conventional tillage without residue retention (Li et al., 2019). Site studies point the same way. In Zambia, aggregate stability reached 41–45% under CA with residue retention and rotation, against 24% under ploughing (Thierfelder and Wall, 2010). The size of the response depends on soil type, with a greater improvement reported on a clay-rich soil than on a clay-poor one (Nyamangara et al., 2014). It also declines with depth, as shown by larger gains at 0–20 cm than at 20–40 cm where straw was returned (Zhang et al., 2020). Long-term maize-based CA in Malawi increased total porosity by 5–15% and improved saturated hydraulic conductivity and plant-available water capacity (Eze et al., 2020).

4.2 Bulk density and compaction

Reports on bulk density under CA are inconsistent. Some studies find higher values than under conventional tillage, others find no difference and others find lower values (Soane et al., 2012; Blanco-Canqui and Ruis, 2018). Part of this variation reflects farm type, since heavy no-till machinery on large farms can compact the topsoil whereas manual or animal-powered smallholder systems rarely do (Cheesman et al., 2016). A global meta-analysis recorded an average increase of 1.4% under no-till with residue retention, still below levels that limit plant growth (Li et al., 2019). Increases are generally attributed to settling of undisturbed soil and to machinery traffic. They need not harm crops, because stable macropores can persist and provide pathways for roots and water (Page et al., 2020).

Effects can also change with depth and time. In an Indian rice–wheat system, no difference appeared in the top 15 cm, but bulk density was higher under the conventional system at 15–30 cm (Mondal et al., 2021). In a long-term study in Ohio, bulk density fell significantly under no-till at 0–15 and 15–30 cm (Islam and Reeder, 2014). In north-western India, zero tillage and permanent raised beds reduced bulk density by 4.3–6.9% in the 0–30 cm layer and lowered penetration resistance by 15.9% and 30.7% relative to conventional tillage (Parihar et al., 2016). Crop rotations with strong taproots and the addition of residues also help limit compaction (Cárceles Rodríguez et al., 2022).

Long-term no-till can nevertheless produce compaction under some conditions (Holland, 2004; Munkholm et al., 2003). Occasional strategic tillage has been proposed to relieve compaction, nutrient stratification and weed pressure in continuous no-till systems (Dang et al., 2015; Wortmann et al., 2010).

4.3 Surface sealing and crusting

Bare soil is vulnerable to raindrop impact, which breaks down aggregates and seals the surface, reducing infiltration and increasing runoff (Cárceles Rodríguez et al., 2022). Residue cover protects against this process, and crusts were absent under CA but present under poorly aggregated conventionally tilled soil in central Mexico (Castellanos-Navarrete et al., 2012). Where residue production is insufficient, as in drier regions or on infertile soils, sealing can still occur under CA, and reduced tillage did not limit crusting in a Mediterranean study (Usón and Poch, 2000; Baudron et al., 2012). Above a certain amount, additional residue brings little extra interception benefit (Baumhardt and Lascano, 1996). Where cover is poor, shallow strategic tillage can break crusts and restore infiltration (Dang et al., 2015).

4.4 Soil moisture and water-use efficiency

Improved aggregation, continuous macropores and surface mulch generally raise infiltration and reduce evaporation, increasing stored soil water under CA (Li et al., 2019; Page et al., 2020). Gains at planting range from roughly 7% to 21% in the long-term studies compiled by Page et al. (2020), and a 50-year Vertisol trial recorded a 13% increase (Page et al., 2019). A meta-analysis found that residue retention raised soil water content by 5.9% compared with residue removal (Zhao et al., 2020). In Malawi, no-till and CA increased soil water by 22 and 18 mm respectively relative to conventional tillage (TerAvest et al., 2015). Under irrigation, residues delay the need for watering, and zero tillage saved 13–21% of irrigation water in South Asia (Gupta and Sayre, 2007). Water-use efficiency also tends to rise under CA (Sun et al., 2018).

The effect is not universal. In rainfed Mediterranean olive orchards, cover crops compete with trees for water, and a modelling study estimated a 25% average reduction in olive transpiration, which early termination of the cover in March can partly offset (Abazi et al., 2013; Durán et al., 2009). In wetter and cooler regions, greater moisture retention can lead to waterlogging that harms crops (Rusinamhodzi et al., 2011; Soane et al., 2012).

4.5 Runoff and soil erosion

Soil loss is a central driver of degradation (Montgomery, 2007). Residue cover and cover crops shield the surface, slow surface flow and improve infiltration, which together reduce erosion (Durán and Rodríguez, 2008). A recent synthesis estimated that conservation practices cut surface runoff and erosion by an average of 67% and 80% relative to conventional practices, with cover crops having the strongest effect (Du et al., 2022). In semi-arid rainfed India, no-till reduced runoff by 16.2% and soil loss by 37.2% (Kurothe et al., 2014). The protective effect scales with the amount of residue. A review reported that residues of 1.5–4.5 t dry matter ha^{-1} lowered runoff by about 50% and 2–4 t ha^{-1} reduced erosion by about 80% compared with bare soil, with the required amount depending on slope and rainfall (Ranaivoson et al., 2017). On Mediterranean hillslopes, combining minimum tillage with plant strips reduced erosion and runoff by about 36% and 39% in almond and vineyard orchards compared with minimum tillage alone (Cárceles et al., 2021).

4.6 Soil temperature

Surface residues and cover crops moderate soil temperature by reflecting radiation and insulating the soil, lowering maximum and raising minimum temperatures near the surface (Blanco-Canqui and Ruis, 2018; Cárceles Rodríguez et al., 2022). Daytime soil temperatures under zero tillage with residue were 2–8 °C lower than under conventional tillage in a Brazilian sugar-cane study (Oliveira et al., 2001). Such cooling may benefit crops in hot regions (Steward et al., 2018). In cooler climates it can delay germination and development. Straw retention delayed winter wheat by up to seven days and cut average grain yield by 7% on the North China Plain (Chen et al., 2007), and non-tilled soils were 0–1.5 °C cooler than ploughed soils in north-east China when residue was not returned (Shen et al., 2018). Conversely, vegetative cover or stubble can keep soils warmer in winter and reduce frost depth (Kahimba et al., 2008).

V. Effects of Conservation Agriculture on Soil Chemical Properties

5.1 Soil organic carbon

The amount of SOC in a soil is the balance between organic inputs and losses through erosion, decomposition and leaching, so the effect of CA depends on how it alters each term (Page et al., 2020). Reduced tillage lowers the turnover of macroaggregates and protects particulate organic matter, as in a Brazilian Acrisol where estimated turnover times were 17 years under conventional tillage and 36 years under no-till CA (Bayer et al., 2006, as summarised by Page et al., 2020). Residue retention and diversified rotations raise carbon inputs, and root inputs of different species have been closely related to SOC stocks (dos Santos et al., 2011). A meta-analysis of paired data found that no-till and reduced tillage with residue retention

increased SOC stocks in the 0–30 cm layer by about 13% and 12% respectively compared with conventional tillage (Li et al., 2020). Differences in carbon input are considered the main explanation for variability in SOC storage between no-till and inversion tillage (Virto et al., 2012).

Published rates of change are highly variable (Table 1). Reported values range from a small loss in the midwestern United States (Christopher et al., 2009) to a gain of nearly 1 Mg ha^{-1} yr^{-1} in tropical Brazil (Bernoux et al., 2006), and one global meta-analysis found no significant effect of no-till (Luo et al., 2010). Tillage can sometimes store as much or more carbon, for instance where inversion buries residues in cool, moist conditions with poor aeration (Christopher et al., 2009; Page et al., 2020). Climate and soil characteristics strongly shape where no-till can store carbon (Ogle et al., 2019), and benefits may only be realised over the long term (Six et al., 2004).

TABLE 1
EXAMPLES OF REPORTED SOC CHANGE FOLLOWING ADOPTION OF CA (NO-TILL WITH RESIDUE RETENTION, WITH OR WITHOUT CROP DIVERSIFICATION)

Region	SOC change (Mg ha^{-1} yr^{-1})	Source
Midwestern USA	−0.15	Christopher et al. (2009)
Central USA	+0.40	Johnson et al. (2005)
Mediterranean regions	+0.44	Aguilera et al. (2013)
Spain	+0.51	González-Sánchez et al. (2012)
Tropical Brazil	+0.93	Bernoux et al. (2006)
China	+0.25	Du et al. (2017)
Sub-Saharan Africa	+0.37	Powlson et al. (2016)
Indo-Gangetic Plains	+0.54	Powlson et al. (2016)
Worldwide (tropical / temperate)	+0.86 / +0.17	Mangalassery et al. (2015b)

Values are as compiled by Page et al. (2020, Table 1) from the cited studies; depth and duration differ between studies, so values are not strictly comparable.

Gains are concentrated near the surface. Global analyses indicate that no-till raised SOC storage mainly in the upper 10 cm (Luo et al., 2010; Mondal et al., 2020), and a maize–mustard rotation showed higher SOC under CA at 0–15 and 15–30 cm but not at 30–45 cm (Pooniya et al., 2021). Sampling the whole plough layer is therefore needed for a fair comparison (VandenBygaart and Angers, 2006). Cover crops can add to the effect. Four years of cover crops in a Spanish olive orchard raised soil organic matter by 10.9–14.3 Mg ha^{-1} in the top 40 cm (Repullo-Ruibérriz de Torres et al., 2021), and long-term CA with cover crops has been linked to increased SOC in Italian cropping systems (Camarotto et al., 2020). Whether CA delivers climate mitigation through SOC in the tropics has also been questioned (Powlson et al., 2016).

5.2 Soil pH

Changes in pH under CA are usually confined to the topsoil and depend on residue chemistry, initial pH, buffering capacity and nitrogen management (Butterly et al., 2013; Page et al., 2020). Surface accumulation of organic matter and organic acids, together with nitrification and root exudation, commonly acidifies the upper layer under no-till (Limousin and Tessier, 2007; Sithole and Magwaza, 2019). Magnitudes vary. In semi-arid environments without fertiliser or lime, changes were about 0–0.3 units after a decade or more (Page et al., 2020), whereas in a Brazilian system with legume rotations and mineral nitrogen, pH fell by 0.4 to 1.5 units (Vieira et al., 2009). A study across the eastern Gangetic plains found pH tended to decline under zero tillage, particularly in acidic soils (Sinha et al., 2019).

Other studies report the opposite. In Zambia, pH was 6.18 under CA and 5.62 under conventional practice after seven years, with higher SOC and nodulation (Muchabi et al., 2014). The buffering effect of accumulated organic matter is the usual explanation for increases, especially in acid soils (Cárceles Rodríguez et al., 2022).

5.3 Cation exchange capacity

CEC is mainly an inherent property controlled by clay content and mineralogy, but organic matter and pH can modify it (Page et al., 2020). Where CA raises SOC, extra negative charge generally increases CEC (Sá et al., 2009). In a long-term South

African study, CEC under conventional tillage was clearly lower than under rotational tillage or no-till (Sithole and Magwaza, 2019). Several studies found no effect, including twenty maize trials in Mexico and a study in Morocco (Fonteyne et al., 2021; Mrabet et al., 2012), which may reflect short trial duration or local soil conditions. Others recorded lower CEC under no-till, attributed to a pH drop that reduced pH-dependent exchange sites (Thomas et al., 2007; Limousin and Tessier, 2007). Direction and magnitude therefore remain site-specific.

5.4 Nutrient dynamics, stratification and losses

Where CA raises residue and organic matter inputs, soil stocks of nitrogen, phosphorus, potassium and several other nutrients often increase (Page et al., 2020; Cárceles Rodríguez et al., 2022). Greater total stocks do not always mean greater plant-available nutrients. Soon after conversion, available nitrogen may fall because mineralisation slows and cereal residues with high carbon-to-nitrogen ratios immobilise nitrogen, so additional fertiliser may be required (Thompson, 1992; O'Leary and Connor, 1997; Sithole and Magwaza, 2019). Legume residues tend to raise mineral nitrogen more than cereal residues (Ranaivoson et al., 2017). A new balance between carbon and nitrogen supply may be reached with time (Page et al., 2020).

Without soil mixing, immobile nutrients such as phosphorus and potassium accumulate at the surface (Mrabet et al., 2012; Deubel et al., 2011). In dry regions, drying of the surface layer can make these nutrients inaccessible to roots (Mrabet et al., 2012; Page et al., 2020). Wetter, denser soils under CA can also increase nitrogen loss through denitrification (Rochette, 2008), and more infiltration can increase leaching of soluble nutrients (Page et al., 2020). On the other hand, CA can reduce nutrient export through runoff and sediment, and cover crops intercept nitrate that would otherwise leach, with reductions of 65–70% reported in one vegetable system compared with fallow (Wyland et al., 1996). Permanent cover in orchard alleys raised SOC and nitrogen but was linked to lower available phosphorus (Morugán et al., 2020).

VI. Effects of Conservation Agriculture on Soil Biological Properties

Soil organisms drive aggregation, aeration, nutrient cycling and disease suppression, and intensive agriculture tends to erode soil biodiversity (Cárceles Rodríguez et al., 2022). Biological indicators respond quickly to management and are therefore valuable for early detection of change, although microbial indicators must be interpreted with caution because their meaning varies among soils (Fierer et al., 2021).

6.1 Microbial biomass and diversity

Greater SOC under CA supplies energy to microorganisms, and improved aggregation, moisture and temperature can favour larger populations (Page et al., 2020). A global meta-analysis of 96 paired experiments showed higher microbial biomass carbon and nitrogen and a higher microbial quotient under no-till with residue retention (Li et al., 2018). Reported increases in microbial biomass carbon range from a few percent to more than 100% (Table 2). Zero tillage with residue retention increased microbial biomass carbon by 29% and 56% and nitrogen by 27% and 84% in a rice–wheat system, compared with conventional tillage with residue removal (Choudhary et al., 2018). The effect is often limited to the surface layer, as in a maize system where differences were significant only at 0–10 cm (Spedding et al., 2004).

Table 2
Examples of increases in soil microbial biomass carbon under CA relative to conventional systems

Location	Average change in MBC (%)	Source
Australia (17 years)	+150	Pankhurst et al. (2002)
Mexico (25 years)	+94	González-Chávez et al. (2010)
Mexico (12 years)	+43 to +98	Govaerts et al. (2007)
China (7 years)	+20	Zhang et al. (2012), as compiled in Page et al. (2020)
India (3 years)	+3 to +27	Somasundaram et al. (2019)

Values are as compiled by Page et al. (2020, Table 3).

Diversity also tends to improve. Fungi in particular benefit from the absence of tillage (Helgason et al., 2010), and bacterial diversity was greater under conservation tillage in northern China (Wang et al., 2016) and in French soils with minimal tillage (Legrand et al., 2018). A 14-year French trial found improved biomass and biodiversity of soil microorganisms under CA

(Henneron et al., 2015). Crop management matters as well, because soils under no-till maize with residue removal showed reduced bacterial diversity relative to no-till wheat with residue retained (Ceja-Navarro et al., 2010). Results are not uniformly positive, and microbial composition does not always track gains in physical quality, which points to the influence of other edaphic and management factors (Cárceles Rodríguez et al., 2022).

6.2 Soil enzyme activities

Enzyme activities indicate the potential of soil to decompose organic matter and mineralise nutrients. β-Glucosidase, N-acetylglucosaminidase and phosphatase are commonly used to represent carbon, nitrogen and phosphorus cycling (Cárceles Rodríguez et al., 2022). Enzyme activities respond strongly to cropping system and disturbance, and no-till with diversified rotations has enhanced activity in surface soil (Cárceles Rodríguez et al., 2022). In a rice–wheat system, zero tillage with residue mulch raised dehydrogenase, cellulase and alkaline phosphatase activities by 23%, 34% and 14% relative to conventional tillage (Sharma et al., 2019), and enzyme activity increased by 5–18% under no-till with residues in north-western India (Banerjee et al., 2017). CA significantly raised dehydrogenase, alkaline phosphatase and urease activities in a maize–mustard rotation (Pooniya et al., 2021). Protease and phosphatase activities increased after only two years of minimum tillage (Kandeler et al., 1999), and zero tillage with legume cover enhanced several enzyme activities in Mexico (Roldán et al., 2003). Zero tillage also raised β-glucosidase and microbial biomass in rice cultivation (Pandey et al., 2014). The mechanisms invoked are more microbial biomass, more substrate and less disturbance (Sinsabaugh et al., 2008), and greater enzyme activity linked to nitrogen and phosphorus cycling was recorded under CA in a United States cotton system (Mbuthia et al., 2015). Zero tillage effects on enzyme activity have also been examined in temperate soils (Mangalassery et al., 2015a).

6.3 Earthworms and other macrofauna

Earthworms are ecosystem engineers that influence nutrient cycling, aggregate stability and the habitat of other soil invertebrates (Cárceles Rodríguez et al., 2022). Tillage injures them, disrupts their burrows, exposes them to predators and removes food sources, so populations are often greater under CA, and the effect grows with the duration of the system (Chan, 2001; Kladivko, 2001; Page et al., 2020). A global meta-analysis found abundance and biomass of earthworms more than doubled with reduced disturbance on average, with the largest effects in warm temperate zones, fine-textured and clay-rich soils (above 35% clay) and low pH soils (below 5.5) (Briones and Schmidt, 2017). Reduced tillage raises functional diversity and the density of anecic earthworms (Pelosi et al., 2014; Henneron et al., 2015). In a long-term Zambian trial, termites and earthworms were more abundant under CA (Muoni et al., 2019). Not every study agrees. Reduced tillage with green manures did not increase earthworms in a Mediterranean organic system, where organic fertilisation was more influential (Baldivieso-Freitas et al., 2018).

6.4 Soil respiration

Soil respiration reflects microbial metabolic activity and is widely used as a biological indicator (Bünemann et al., 2018). The effect of CA is inconsistent. Several studies found no significant difference from conventional tillage (Cooper et al., 2020; Ye et al., 2021), possibly because tillage alters the timing of CO_2 emissions more than the total, so seasonal sampling is needed to assess it properly (Gyawali et al., 2022). Others reported higher respiration under no-till, including a 12-year study that recorded greater microbial respiration (Nunes et al., 2018). Respiration has been strongly and positively related to SOC ($r = 0.84$) in a rice–wheat system (Bera et al., 2018). Practices that increase organic carbon inputs and crop diversity are generally expected to improve microbial activity (Cárceles Rodríguez et al., 2022).

6.5 Soil-borne diseases

Disease responses to CA are mixed. Residues can shelter pathogens between crops, and reduced disturbance, higher moisture and cooler soil can favour them. Pathogens reported to increase under no-till or residue retention include those causing take-all, crown rot, tan spot and Rhizoctonia root rot (Bockus and Shroyer, 1998; Page et al., 2020). When reduced tillage and residue retention are combined with diversified rotations, however, increases are much smaller, and greater biological diversity can increase populations of disease-suppressive organisms (Peters et al., 2003; van Bruggen et al., 2006). For example, take-all can decline as antagonistic Pseudomonas populations rise (Paulitz et al., 2010).

VII. SOIL ORGANIC CARBON AS AN INTEGRATING DRIVER AND THE ROLE OF CONTEXT

Across the three groups of properties, SOC acts as a common driver. Higher SOC supports aggregate stability, which in turn raises infiltration, water storage and erosion resistance (Section 4). It increases cation exchange and nutrient reserves and

buffers pH (Section 5), and it supplies energy and habitat for microbial and faunal communities and their enzymes (Section 6). Gains in all three tend to occur together where CA raises SOC, and Page et al. (2020) conclude that where SOC increases, improvements in structure, water, nutrients, microbial biomass and diversity, and yield often follow. The inverse is also true. Where residue production is low, because of infertile soils, drought, residue removal for feed or fuel, or weed and pest problems, the carbon, structural and biological benefits are weakened (Page et al., 2020).

Yield responses show the same dependence on context. A global meta-analysis found that full CA reduced yields on average by 2.5%, with larger losses (9.9%) for no-till alone and 5.2% for no-till with residue retention, but yield gains of 7.3% in rainfed dry climates, and yield penalties tended to diminish over time (Pittelkow et al., 2015). Poor drainage, cold soils, inadequate weed control and lack of suitable equipment are common causes of yield loss (Rusinamhodzi et al., 2011; Page et al., 2020). Where yields are maintained, profitability usually improves through savings in labour, fuel and, in irrigated systems, water (Page et al., 2020; Vastola et al., 2017). Evidence on yield stability is mixed, with some analyses indicating benefits, especially with cover crops, and others finding no difference (Williams et al., 2018; Knapp and van der Heijden, 2018).

TABLE 3
SUMMARY OF REPORTED EFFECTS OF CA ON SOIL PROPERTIES AND THE CONDITIONS THAT MODIFY THEM

Property	Typical response under CA	Conditions where gains fail or reverse	Key sources
Aggregate stability	Increase, strongest in topsoil	Low residue input; clay-poor soils respond less	Li et al. (2019); Thierfelder and Wall (2010)
Bulk density	Inconsistent; small increase on average	Heavy machinery; long-term no-till compaction	Li et al. (2019); Parihar et al. (2016)
Soil water	Increase in stored water; higher water-use efficiency	Cover crops competing for water; waterlogging in wet, cool areas	Page et al. (2019); Abazi et al. (2013)
Runoff and erosion	Strong decrease	Insufficient residue cover; steep slopes	Du et al. (2022); Ranaivoson et al. (2017)
Soil temperature	Moderated; cooler in summer	Delayed crop development in cool climates	Oliveira et al. (2001); Chen et al. (2007)
SOC	Increase, mainly in surface layers	Low biomass; cool, moist, poorly aerated soils; shallow sampling	Page et al. (2020); Luo et al. (2010)
pH	Surface acidification or buffering	Legume rotations and N fertiliser; acid soils	Vieira et al. (2009); Muchabi et al. (2014)
CEC	Increase, no change or decrease	pH decline; short trials	Sá et al. (2009); Fonteyne et al. (2021)
Nutrients	Higher total stocks; surface stratification	N immobilisation early on; dry surface layers	Thompson (1992); Mrabet et al. (2012)
Microbial biomass and diversity	Increase, often surface-limited	Residue removal; monocultures	Li et al. (2018); Choudhary et al. (2018)
Enzyme activities	Generally increase	Variable with soil and system	Sharma et al. (2019); Pooniya et al. (2021)
Earthworms	Increase, grow with duration	Some Mediterranean organic systems	Briones and Schmidt (2017); Baldivieso-Freitas et al. (2018)
Respiration	Inconsistent	Timing of sampling	Nunes et al. (2018); Gyawali et al. (2022)

Synthesis by the author of the studies cited in Sections 4–6.

VIII. CHALLENGES AND FUTURE PERSPECTIVES

Technical, social and economic constraints all shape whether CA delivers its soil benefits. Agronomic problems include weed, pest and disease control without tillage, nutrient stratification, lower nitrogen availability, poor crop establishment with unsuitable seeders, and surface crusting or compaction (Dang et al., 2015; Page et al., 2020). Social and institutional barriers include cultural attitudes towards tillage, competing uses of residues, limited access to information, and absence of markets for diversified crops or of affordable inputs and machinery (Brown et al., 2017; Andersson and D'Souza, 2014; Bhan and Behera, 2014).

Several research directions follow from the evidence reviewed here. First, CA systems need to be adapted to local conditions through suitable rotations, cover crops, seeding equipment and fertiliser use (Thierfelder et al., 2018; Vanlauwe et al., 2014; Giller et al., 2015). Second, strategic or occasional tillage deserves more study to clarify its optimum frequency and timing and its effect on SOC and biology (Kirkegaard et al., 2014; Dang et al., 2018). Third, comparisons should sample the whole plough layer, include seasonal measurements and report duration and residue input, because depth, method and timing strongly affect conclusions (VandenBygaart and Angers, 2006; Gyawali et al., 2022). Fourth, better and more standardised indicators and indices are needed to evaluate soil health and guide management (Lehmann et al., 2020; Bünemann et al., 2018). Finally, long-term field experiments remain essential given the multi-year transition before benefits appear (Stagnari et al., 2014).

IX. CONCLUSIONS

The evidence reviewed indicates that, where it is well designed and adapted to local conditions, conservation agriculture improves soil physical condition by enhancing aggregation, infiltration, water storage and erosion control; strengthens chemical fertility through higher organic carbon and nutrient stocks, mainly in the topsoil; and stimulates biological activity through greater microbial biomass, enzyme activity and macrofauna. These responses are tightly linked through SOC. At the same time, effects on bulk density, pH, CEC and respiration are inconsistent, and several risks, including nutrient stratification, compaction, sealing, waterlogging, cooler soils and weed or disease pressure, can limit success where residue production is low or climates are cold and wet. Benefits often take years to develop. CA should therefore be treated as a flexible, locally tailored set of practices, supported by research, extension and institutional backing, rather than as a uniform recipe.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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