Conservation agriculture impact on soil and crop productivity: a review of long-term field trials

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Abstract. A large scientific body advocates for conservation agriculture (CA) as a means of tackling climate change-related challenges of future agriculture. The combined practices of CA are presented as a sustainable farming system of achieving crop production while preserving or improving soil health. However, crops productivity under CA remains controversial and of high heterogeneity. Space, namely soil and climatic conditions of the research area, and the time frame of empirical studies are the two factors commonly related to results variability. This paper aimed to understand the effects of long-term (>10 years) implementation of CA in an attempt to minimize time-related uncertainties and help find the best strategies for incentivizing a wider adoption of CA, as a key contributor in preserving soil resources under climate change.

Key Words: soil health, SOC, bulk density, nutrient cycle, yield variability.

Introduction. There are two approaches to evaluate the performance of agricultural practices. One focuses on the measurable efficiency of cropping systems evaluated through yields and profit margins, equally valid arguments to motivate the activity of economic agents in this area and address global needs in terms of food security. The other involves the benefits of these practices on those ecosystem services (Schipanski et al 2014; Tahat et al 2020; White et al 2017) that directly (soil health, water cycling, pest management) or indirectly (biodiversity, carbon sequestration) affect the cropping system. The second has gained a growing interest among stakeholders (researchers, farmers, and policymakers), justified by the pressure of intensive agricultural practice on agricultural soils (Prăvălie et al 2021).

Enhancing agricultural sustainability by maintaining soil health, conserving soil water, and reducing soil erosion is the focus of a combination of farming practices encompassed in the concept of conservation agriculture (CA) (Kassam et al 2014, 2019). The base of the concept was laid in the 1950's in the United States when researchers testing minimum tillage systems aimed to improve yields of corn monocropping systems (Islam et al 2014). The importance of tillage declined with technological advances in chemical weed control (Cordeau et al 2022), and minimum tillage research expanded through North America, subsequently experiencing commercial expansion in South America and Australia, where large farms could benefit from economies of scale by adopting these practices.

Moreover, these farms also have the agricultural equipment to engage in minimum or no-tillage work (Johansen et al 2012). In the 1960's the no-till system was adopted in agricultural practice in the USA, and in the 1970's it spread to Brazil, where it was developed through research and practice so that from 1990 onwards, international bodies such as FAO, the World Bank or CGIAR became increasingly interested in this agricultural system whose adaptation was subsequently promoted predominantly in African and Asian countries (Kassam et al 2015). The expansion of these practices has been most intense in South and North American countries, Australia and Africa, and had a slower pace in Europe due to geographical and crop heterogeneity (Kertész et al 2014), but also due to farm typology, with 66% of EU-27 farms being small family farms (European Commision 2018).

CA is based on three fundamental pillars (FAO 2023): minimal soil disturbance, usually less than 20-25% of the soil surface; avoiding fallow and permanently covering the soil (>30% of the surface), either using residue of preceding crops or cover crops (especially vegetables or legumes, which can be used as green manure); and crops rotation (annual, bi-annual and perennial), with benefits in terms of weeds, diseases and pest management (Doaei et al 2020; Eslami et al 2014; Gonzalez-Sanchez et al 2015; Pittelkow et al 2015). There is a consensus regarding the advantages of CA practices and a variability of results that raises challenges in their adoption. Numerous empirical studies documented the beneficial influence of reducing soil disturbance, crop rotations, and the use of cover crops on the quality of soil attributes (Chahal et al 2021; Jayaraman et al 2022; Sharma et al 2018). CA practices can control soil erosion (Jacobs et al 2022; Madarász et al 2016; Yadav et al 2017) and increase soil health by maintaining crop residue. The latter improves soil organic carbon and enhances porosity, contributing to water infiltration and reducing evaporation (Blanco-Canqui et al 2007; Hobbs et al 2008; Hok et al 2015; Hu et al 2017; Lal et al 2015). Total organic carbon (TOC) increases were reported at the soil surface (0−25 cm) under conservation tillage (minimum, reduced, and no-tillage), while soil organic carbon and aggregate stability were significantly influenced by reduced and no-tillage in dryland vetch – wheat cropping system (Rahmati et al 2020). Wet aggregate stability and infiltration capacity increased under no-tillage, straw residue, and nitrogen fertilization systems, while soil organic carbon (SOC) recorded no significant differences (0-60 cm depth), and bulk density had a slight increase (Huang et al 2015). Furthermore, research shows how re-adopting conventional tillage (CT) after long-term (12 years) application of no-tillage (CT) can result in soil physicochemical attributes degradation, reducing porosity and water content and increasing bulk density, while using cover crops leads to higher soil moisture (Mubvumba et al 2022).

Rotation of main crops creates biodiversity over time rather than space, while cover crops can help enhance it (McDaniel et al 2014). Both the duration of the rotation and the plant species lead to differences in the effects of rotation on soil characteristics and production yield (Benitez et al 2017; Dury et al 2012). Crop rotation and cover crops have been reported to contribute to diseases and pest management, breaking the life cycle of pathogens. CA practices of no-tillage and cover crops can influence the abundance of fungal communities in correlation to soil pH and bulk density, with minor impacts on soil microbial communities (Narayana et al 2020). However, crop rotation can have a significant influence on the diversity of soil microbiota, while cover crop influence is limited by their short growing period (Chamberlain et al 2020). Some cash crop species can inhibit weed development by allelopathy (Farooq et al 2020; Khanh et al 2005; Kostina-Bednarz et al 2023) cycles. Furthermore, cover crops can suppress weed infestation (Büchi et al 2018; Masilionyte et al 2017; Mirsky et al 2013), especially in no-tillage systems (Eslami et al 2014), and provide habitat for beneficial insects (Bianchi et al 2006; Sharma et al 2018). Crop rotation can break pest cycles (Fanadzo et al 2018), and rotation with cover crops under minimum soil disturbance contributes to improving SOC, soil nitrogen, and water content (Ghimire et al 2019; Haruna et al 2019; Mukherjee et al 2015; Nascente et al 2015). Phosphorus availability can increase due to cover cropping in a cover crop – continuous soybean- conventional tillage system. Moreover, the cover crops scavenged excess ammonium nitrogen (Bragazza et al 2021; Dozier et al 2017), reducing nitrogen (N) leaching by up to 80-90%, depending on cover crop species or mixture, and increase N uptake of cash crops (Kaye et al 2019).

However, some constraints challenge the adoption of CA practices. Pest management, especially in the lack of fungicides and insecticides (Belfry et al 2017), and weed management (Casagrande et al 2016; Johansen et al 2012; Lefèvre et al 2012; Soane et al 2012) arise as major limitations. The latter became more stringent, especially for European agriculture. From the perspective of glyphosate prohibition, estimates indicate a rise in CA practices' costs by up to 40-60% (Pardo et al 2019) and a considerable increase in soil tillage (Wynn et al 2022). Temporarily nutrient immobilization (Alghamdi et al 2022) also represents a challenge in systems with high residue accumulations. Simultaneously, cover crops may compete with cash crops for resources, especially soil water, diminishing yields (Nielsen et al 2016).

Investing in cover crops may also result in higher costs and profitability losses (Kaye et al 2017; Snapp et al 2005). Nevertheless, some studies indicate short-term economic incentives as yield increases of the subsequent crop coupled with economic benefits (Nordblom et al 2023). Others note yield variability with a cost decrease of over 40% (Jacobs et al 2022), while some state that integrating cover crops generates economic benefits over time if they are used as green fertilizers, replacing mineral fertilizers (Jacobs et al 2022; Schipanski et al 2014). The pecuniary outcome varies due to soil and climate conditions but also due to farm management decisions (Bergtold et al 2019). Furthermore, reduced and no-tillage is generally accepted as an economic practice due to reduced labour and fuel costs (Kumara et al 2020; Rudel et al 2016; Thierfelder et al 2017). Additionally, yields' variability (Casagrande et al 2016; Lefèvre et al 2012; Teasdale et al 2007; Vincent-Caboud et al 2017) plays a major decisional role in the adoption of conservation tillage beyond a certain lack of knowledge (Lahmar et al 2010), and the investments in the equipment (Vincent-Caboud et al 2017), thus motivating conventional agricultural practices over CA practices.

Although mechanisms of the soil and plant ecology show the capacity to attain a new balance of the cropping system, the learning curve is time-consuming, and opportunity costs might hinder farmers' decisions. Soil quality benefits are, to some extent, a limitation considering that they are not visible in the short term and are site-specific, with a high field variability in relation with soil and climate parameters (Jacobs et al 2022; Pittarello et al 2021; Swanepoel et al 2018; Welch et al 2016). Extensive reviews also point out some variability of conservation agriculture in terms of positive effects on ecosystem services, pests, disease control, and yields, although highlighting a consistency of CA preserving soil organic matter in the topsoil, reducing runoff, phosphorus losses, and nitrogen leaching (Palm et al 2014; Soane et al 2012). CA was associated with reducing soil degradation (Cárceles Rodríguez et al 2022), improving bulk density, diminishing water evaporation, improving water infiltration and macro-pores, (Haruna et al 2017), but with limited impact on soil water holding capacity (Abdallah et al 2021). Consistency in CA practices in the long term might result in yield increases under favorable conditions (fertile soils, sufficient rainfall, irrigation) as compared to conventional practices, while under restrictive growing conditions (drought, low fertility soils), yield benefits are more easily obtained (Thierfelder et al 2017). Similar trends were found in temperate climates, on low or average fertility soils in northern agricultural areas in Europe, abundant in rainfalls, where yield varied insignificantly (+/-10%) under CA practices, while in dry Mediterranean areas, results revealed 10-15% yield increases (Lahmar et al 2010).

There is still a heterogeneity of results regarding CA effectiveness related to yields, cropping system management, and soil attributes improvement. Moreover, site-specific conditions and the duration of implementing CA practices seem to be key factors causing the variability. Beyond ecosystem services that benefit from CA implementation, the actual effectiveness of the concept should also be addressed through the lenses of a practitioner (farmer) and considering their major motivators in terms of (1) improving soil properties (Casagrande et al 2016; Soane et al 2012; Vincent-Caboud et al 2017), and (2) controlling yields variability (Jacobs et al 2022).

We hypothesize that long-term studies provide a better understanding of the impact of conservation agricultural practices, especially on soil health and, consequently, on cash crop yields. Long-term studies are more valuable in measuring carbon and nitrogen storage (Chahal et al 2021) and changes in soil structure and yields (Nouri et al 2019), as plants might respond differently to the environment over time (Macholdt et al 2019). In the long run, the effects of agronomic treatments are more relevant as plant-soil interaction stabilizes. Therefore, the variability of the results might be reduced (Borrelli et al 2014). From another perspective, short (<10 years) field studies related to minimum soil disturbance practices do not offer an adequate amount of time for soil to achieve equilibrium (Gruber et al 2012). Long-term trials are considered more relevant in evaluating crop yield variability under a CA management system (Borrelli et al 2014; Zhang et al 2015), as the effects of reduced tillage and residue deposition are more visible with time (Hungria et al 2009). This paper aims to review to what extent the long-term implementation of CA practices can influence soil health parameters and consequently improve crop yield variability. In an attempt to minimize the heterogeneity of the findings we also examined the results of meta-analyses in the scope of CA practices.

Results and Discussion

Conservation agriculture and soil health. A well-established advantage of CA is improving soil health. Soil health is a relatively new concept used to express soil quality through a series of physical, chemical, and biological properties responsive to agricultural conditions and practices (Bünemann et al 2018; Cárceles Rodríguez et al 2022; Yang et al 2020). Enhancing soil organic matter content, water infiltration, and nutrient cycling contributes to increasing the soil's capacity to support plant growth and biodiversity, increasing crop production. Soil organic carbon (SOC) is a representative indicator of soil quality, acting as an integrator of soil's physical, chemical, and biological functions (Palm et al 2014; Zhang et al 2015). SOC is an important indicator of soil health and correlates to a lower yield variability (Congreves et al 2017). SOC and soil nitrogen (SN) are positively correlated to soil health indicators. In addition, both indicators are responsible for soil physico-chemical and biological properties variation (Mazzoncini et al 2011) and tend to be higher in no-tillage systems (Cárceles Rodríguez et al 2022; Chahal et al 2021). Soil coverage and residue retention associated with CA management facilitate SOC retention (Abid et al 2009; Ghimire et al 2019; Schmidt et al 2018), and much more SOC mineralization was reduced under minimum tillage, thus protecting the organic matter from microbial decomposition (He et al 2023). However, some studies consider the benefits of improving soil health under CA practices as depending on climate, soil type, and production system (Abdallah et al 2021; Blanco-Canqui et al 2015; Palm et al 2014; Su et al 2021b).

Effect of combined CA practices on soil organic carbon. Two long-term CA studies (21 years and 36 years) conducted in a temperate humid climate (Ontario, Canada) demonstrated that crop rotation and no-tillage (compared to monocropping and conventional tillage) had a positive effect on SOC and microbial activity (Chahal et al 2021). Thus, in the long term, crop rotation with cover crops on the no-tillage background and the use of perennials lead to higher amounts of SOC (Table 1), while using nitrogen fertilizers might accelerate mineralization, therefore affecting SOC accumulation in the top and subsurface soil (0-15 cm). Results are consistent with other long-term research proving that rapid mineralization had a negative effect on soil nitrogen and carbon under conventional tillage (CT) (Anil et al 2022). Under no-till (NT) management, the use of leguminous species proved detrimental to SOC accumulation due to their low C:N ratio that favors decomposition. In warm and humid conditions, 12 years of research on the effects of tillage, rotation (corn, cotton, soybean), and cover cropping showed that SOC content was positively correlated with monocropping or intercropping high lignin species (corn, cotton), while introducing soybean to the rotation, or using winter cover crops exhibit limited capacity of supporting soil carbon accumulation (Jagadamma et al 2019). These effects were observed in the top soil layer (<5 cm) and disappeared at 0-15 cm. Similar results were reported in a humid subtropical climate over 15 years of applying CA cropping systems (with no-tillage, crop rotation, and bio-covers) (Ashworth et al 2020). SOC content was influenced by crop rotation with cash crop species with a high lignin and residue biomass (corn), whereas crop rotation with soybean and high-nitrogen cover crops generated more labile residue, favoring microbial decomposition.

A 17-year study in a subtropical climate (dos Santos et al 2011) highlighted the role of roots in increasing carbon stock in the subsurface layer (5-20 cm), especially in cropping systems without the return of crop residue. The results showed that every three years alfalfa and maize intercropping, followed by rotations with forage crops (*Lolium multiflorum* Lam.) and legume cover crops (*Vicia villosa* Roth) have higher carbon sequestration potential compared to a wheat-soybean cropping sequence (Table 1). Within similar pedologic and climate limits (on clay soil - Oxisol situated in the sub humid tropical climate of Brazil), after 19 years, no-tillage and winter cover crops facilitated SOC storage in the upper soil layer (0-10 cm). In the humid subtropical climate of the Tennessee Valley, minimum soil disturbance and crop rotation significantly increased SOC (Motta et al 2007). Double cropping (cotton-wheat/soybean) with wheat used as a cash crop resulted in higher SOC values compared to wheat used as a cover crop. Cover crops also generated higher residue when conventional tillage was applied. Soil carbon improvement was noted in the top 3 cm of soil and, after 12 years of CA practices, was mainly attributed to tillage rather than to cover cropping. A similar influence was noted after 47 years of practicing CA in a temperate climate on Haplic Luvisol (24% clay, 65% silt, and 9% sand) (Mary et al 2020). Reduced tillage treatments (shallow and no-tillage) had higher SOC concentrations in the upper layers (0-5 cm and 5-10 cm) and lower concentrations in the deeper layers (below 10 cm) compared to CT. The change in SOC storage was attributed to the priming effect rather than the changes in physical soil disturbance.

Similarly, 12 years of research (Olson et al 2014) conducted on silt loam soil in southern Illinois found that the use of cover crops increased SOC stock for different soil disturbance intensities (no-tillage > chisel > plow) as a result of increasing soil surface residue and reducing soil erosion. Moldboard plowing resulted in lower total organic carbon on the Canisteo clay loam and Webster silty clay loam soil in Iowa (humid continental climate) for both 31 years of corn-soybean rotation and 26 years of corn monocropping, attributed to lower microbial activity and lower potentially mineralizable nitrogen under intensive tillage (Karlen et al 2013). An 11-year study in the North China Plain (brown loam soil) suggested that SOC accumulation in the temperate semi-humid monsoon climate was influenced by climate variations, namely precipitation increase that led to an increase in crop residue returned to the soil. Overall, SOC was inversely related to soil disturbance, with the highest value obtained under NT for a wheat-corn rotation with residue return (Xu et al 2019).

In the Mediterranean climate, a 15-year study on CA practices with cover crops and mineral nitrogen fertilization reported that CT provides higher C inputs compared to NT (Mazzoncini et al 2011), favoring increased biomass yield for cash crops and cover crops. Nevertheless, SOC concentration in the top 10 cm layer was improved by NT practice due to a lower soil organic matter mineralization rate, attributed to a drier climate. High nitrogen-rich legume residue provided the highest increase in organic matter and nitrogen supply (Mazzoncini et al 2011). In hot and dry regions (California, USA), but with applied irrigations, NT and cover cropping over 15 years resulted in higher levels of organic carbon, nitrogen supply, and an increased biological activity, but with no interaction among practices (Mitchell et al 2017). As previous empirical studies demonstrated, the carbon stock was higher at the surface layer (0-15 cm). In a Mediterranean climate, on Panoche clay loam soil (California Central Valley), 15 years of cover crops and NT practices increased SOC by 12-53% in the top 30 cm of soil, while the highest concentration was found at the soil surface (0–5 cm) (Schmidt et al 2018).

After 23 years of CA practices in the Mediterranean climate of Italy, testing conservation tillage on silt loam soil resulted in a slight SOC accumulation but with no significant differences over conventional tillage (Piazza et al 2020). The result was attributed to the low amount of aboveground residue and roots (<2.9 t ha^{-1}), as some research (Kong et al 2005) identified a minimum of 8.9 t/ha residue for CA to improve SOC in the Mediterranean area. In addition, reduced tillage completed by nitrogen fertilization on soils specific to the dry climate, characterized by anaerobiosis conditions and low water content, prevented the microbial decomposition of the organic matter, favoring SOC immobilization. The dynamic was attributed to the change in the microbial community (bacteria vs. fungi or dormant vs. active organisms) (Piazza et al 2020).

Table 1

Reported effects on soil organic carbon (% change vs. control) by long-term CA practices, soil texture and depth

Duration	*Soil*	*Multiannual prec. (mm)*	*CA treatment*	*Depth (cm)*	*Organic carbon change %*	*References*
17 yrs.	Oxisol, sandy clay	1700-1800	NT+C-A[1]	0-20	+16.7*^{s}	dos Santos et al (2011)
15 yrs.	Silt loam	107, 114[3]	NT+AWp[2] NT+HV[2]	0-15	+4.6****^{ns} +1.7****^{ns}	Ashworth et al (2020)
15 yrs.	Typic Xerofluvent, loam soil	864	HLN[2]	0-10	+10.5**^{s}	Mazzoncini et al (2011)
				10-30	+9.1**^{s}	
15 yrs.	Panoche clay loam	210	CC[2]	0-15	+19.8*^{s}	Mitchell et al (2017)
				15-30	+12.5*^{s}	
			NT	0-15	+52.7*^{s}	
				15-30	+13.2*^{s}	
19 yrs.	Oxisol, high clay content	1200-1500	NT	0-5	+34.0**^{s}	Calegari et al (2008)
				5-10	+3.8**^{ns}	
			RD[2]	0-10	+19.9**^{ns}	
21 yrs.	Orthic Humic Gleysol, clay loam	895	C-S	0-15	-0.31**^{ns}	Chahal et al (2021)
			C-S-W		-0.24**^{ns}	
			C-S-W-RC[2]		-0.22**^{ns}	
			S-W		+0.36**^{ns}	
			S-W-RC[2]		+0.47**^{s}	
36 yrs.	Gleyed Melanic Brunisol, silt loam	-	C-C-O-RC[2]-B-RC[2]	0-15	+0.18**^{ns}	Chahal et al (2021)
			C-C-O-B		-0.08**^{ns}	
			C-C-S-W		0.0**^{ns}	
			C-C-S-W-RC[2]		-0.07**^{ns}	
			C-C-S-S		-0.31**^{ns}	
			C-C-A-A		+0.04**^{ns}	
21 yrs	Decatur silt loam soil	1353	NT	0-3	+126.5**^{s}	Motta et al (2007)
12 yrs			NT+T-W[2]		+76.6**^{s}	
47 yrs	Haplic Luvisol, silt clay	635	ST	0-5	+54.2**^{s}	Mary et al (2020)
			NT		+68.1**^{s}	
			ST	5-10	+13.5**^{s}	
			NT		+2.7**^{ns}	
			ST	10-15	-17.0**^{s}	
			NT		-17.8**^{s}	
11 yrs	Brown loam	697	NT	0-20	+22.6**^{s}	Xu et al (2019)
			SB		+12.3**^{s}	
			CT+CR		+6.6**^{s}	
			NT+CR		+23.6**^{s}	
			SB+CR		+33.0**^{s}	
12 yrs	Typic Hapludoll, clay loam	520	RT+CR	0-20	+5.3**^{ns}	Zhang et al (2015)
			NT+CR		+1.8**^{ns}	
40 yrs	Silt loam	-	NT	0-6	+46.6***^{s}	Kinoshita et al (2017)
			NT+CR		+80.9***^{s}	
			CT+CR		0.0***^{ns}	
			NT	18-30	-7.2***^{ns}	
			NT+CR		+29.6***^{s}	
			CT+CR		+15.8***^{ns}	
23 yrs	Fluvisol, silt loam	-	CT+N	0-15	-32.4**^{s}	Piazza et al (2020)
			MT		+20.9**^{s}	

Duration	Soil	Multiannual prec. (mm)	CA treatment	Depth (cm)	Organic carbon change %	References
			MT+N	15-30	+41.7**^{s}	
			CT+N		-13.5**^{ns}	
			MT		-8.8**^{ns}	
			MT+N		68.1**^{s}	
12 yrs	Typic Fragiudalf, silt loam	644	CT+HV^{2}/R^{2}	0-15	0.0**	Olson et al (2014)
			CP		+7.4**^{s}	
			CP+HV^{2}/R^{2}		+25.4**^{s}	
			NT		+39.2**^{s}	
			NT+HV^{2}/R^{2}		+67.7**^{s}	
			CT+HV^{2}/R^{2}	15-75	+4.5**^{s}	
			CP		-10.7**^{s}	
			CP+HV^{2}/R^{2}		-0.4**^{s}	
			NT		+1.2**^{s}	
			NT+HV^{2}/R^{2}		+21.4**^{s}	
31 yrs	Clay loam	-	CP	0-5	+19.0*^{s}	Karlen et al (2013)
			SD		+33.3*^{s}	
			RT		+28.6*^{s}	
			NT		+33.3*^{s}	
			CP	5-15	+9.5*^{s}	
			SD		+14.3*^{s}	
			RT		+9.5*^{s}	
			NT		+4.8*^{ns}	

*TOC - total organic carbon, **SOC – soil organic carbon,***SOM – soil organic matter, ****C:N ratio, s/ns – significant/ not significant based on authors' analysis, 1 classic 3 years intercropping, 2 used as cover crop, 3 two locations with no differences across, C – corn, A – alfalfa, W - wheat, O – oat, B – Barley, T – cotton, AWp – Austrian winter pea, HV – hairy vetch, HLN - high nitro-gen supply legume cover crop, NT – no tillage, ST - shallow tillage, CC – cover crop mix, RD – radish, RC – red clover, SB – subsoiling, CR – cash crop residue returned to the soil, RT- ridge till-age, MT – minimum tillage, N – mineral nitrogen fertilization, CP – chisel plow tillage, HV/R – Hairy vetch/ cereal rye, SD – spring disking

A recent meta-analysis (Rietra et al 2022), compiling other meta-analyses on different conventional and conservative agricultural practices, concluded that carbon sequestration and SOC are driven by the use of cover crops and conservation tillage (reduce, zero, no-tillage). Soil carbon sequestration was enhanced by agricultural practices that involved rotations with species with a high lignin content (dos Santos et al 2011; Jagadamma et al 2019), thus reducing the environmental impact of agriculture. Different critical reviews also captured the impact of CA practices on increasing soil organic carbon, improving nitrogen stocks, and biological activity (Bohoussou et al 2022; Li et al 2018; Mahal et al 2018). Data collected and analysed in a critical review (meta-analysis) concerning crop residue influence on soil agroecological functions (Ranaivoson et al 2017) indicated that the amount of residue used as mulch had a weak influence on SOC and soil microbiological activity. Nevertheless, the same study showed that crop residue reduced water evaporation when 30% of the soil was covered, corresponding to 8 t/ha of residue, and a 50% coverage rate (4 t/ha residue) significantly reduced weed emergence and biomass.

Other meta-analyses of SOC dynamic under CA resulted in less firm conclusions over the positive relation between SOC and minimum soil disturbance (reduce or zero tillage), attributing the variation to soil and climate characteristics (Tadiello et al 2023) and highlighting the role of crop residue (Xiao et al 2021). A meta-analysis on the influence of cover crops over SOC stocks resulted in a linear function suggesting an average annual carbon sequestration rate of 0.32 t/ha, without any significant variables between climatic area, tillage type, or cover crop species (Poeplau et al 2015).

Effect of combined CA practices on soil compaction and nutrients availability. Lack of vegetation and excessive soil manipulation negatively affect soil structure, leading to its compaction, subsequently influencing soil health and diminishing crop yields. Soil compaction, quantified by porosity or bulk density, is closely linked to soil's structural stability and depends on pedogenic processes and agricultural management factors (Haruna & Nkongolo 2020). When the soil is compacted the pore spaces between soil particles are reduced, disabling the exchange of gases and affecting root penetration. On clayey soils (Cambisols, Luvisols, and Chernozems), plant residue accumulation favors the formation of very stable microaggregates and promotes microbial activity, thus enhancing the stability of macroaggregates (Blume et al 2016).

Long-term agricultural practices reducing soil disturbance show high variability in improving soil compaction closely related to soil type, enhanced when tillage was not coupled with practices favoring organic matter accumulation, namely rotation with cover crops and residue incorporation (Table 2). On soils with a fine texture (clayey soils), reduced tillage is effective in reducing bulk density in the surface layer (0-5 cm) (Karlen et al 2013), or the subsurface layer (0-15 cm) when completed by cover crops residue incorporation (Mitchell et al 2017), but not for deeper layers or the entire soil profile (0-20 cm, 0-30 cm) (Mitchell et al 2017; Zhang et al 2015). Furthermore, reduced tillage was reported to diminish bulk density in the surface layer (0-10 cm) of a Haplic Luvisol (24% clay, 65% silt, 9% sand) but was not effective at 10-20 cm. The effect was attributed to lower mechanical incorporation of residue (Mary et al 2020). CA practices effectiveness in improving soil compaction is strongly reflected in soils with a balanced mixture of particle sizes, where different forms of reduced tillage and residue incorporation (Table 2) contribute to a decrease in bulk density even at lower depths (Mazzoncini et al 2011).

Table 2

Reported effects on soil bulk density (% change vs. control) by long-term CA practices, soil texture and depth

Duration	*Soil*	*Multiannual prec. (mm)*	*CA treatment*	*Depth (cm)*	*BD change %*	*References*
17 years	Oxisol, sandy clay	1700-1800	NT+C-A^{1}	10-20	-7.1^{s}	dos Santos et al (2011)
15 yrs.	Typic Xerofluvent, loam soil	864	HLN^{2}	10-30	-0.7^{s}	Mazzoncini et al (2011)
15 yrs.	Panoche clay loam	210	CC^{2}	0-15	-4.2^{s}	Mitchell et al (2017)
			NT	0-15	$+8.1^{s}$	
				15-30	$+14.8^{s}$	
34 yrs.	Lexington silt loam	1350	NT	15-30	$+3.3^{s}$	Nouri et al (2019)
12 yrs.	Typic Hapludoll, clay loam	520	RT+CR	0-20	$+0.0^{ns}$	Zhang et al (2015)
			NT+CR		$+1.5^{ns}$	
40 yrs.	Silt loam	-	NT	0-6	-4.3^{ns}	Kinoshita et al (2017)
			NT+CR		-8.0^{s}	
			CT+CR		-2.2^{ns}	
			NT	18-30	-0.6^{ns}	
			NT+CR		-7.6^{s}	
			CT+CR		-4.5^{ns}	
31 yrs.	Clay loam	-	CP	0-5	-23.1^{s}	Karlen et al (2013)
			SD		-23.1^{s}	
			RT		-15.4^{s}	
			NT		-23.1^{s}	

BD – bulk density, s/ns – significant/ not significant based on authors' analysis, 1 classic 3 years intercropping, 2 species used as cover crop, C – corn, A – alfalfa, HLN - high nitrogen supply legume cover crop, NT – no tillage, CC – cover crop mix, CR – cash crop residue returned to the soil, RT- ridge tillage, CP – chisel plow tillage, SD – spring disking.

Forty years of CA practices (no-tillage and residue retention) applied to a continuous maize cropping system on silt loam soil and in a humid continental climate showed the improvement of soil physical properties and nutrient availability at different soil depths. The empirical study presented a significant effectiveness of CA practices in reducing bulk density at the soil surface (0-6) and the transition layer (18-30), in strong correlation to organic matter accumulation. No-tillage and residue retention also improved soil aeration, water infiltration, and drainage in the transition layer (18-30 cm) (Kinoshita et al 2017).

Another long-term research on Lexington silt loam soil in the sub-humid climate of the South-eastern USA, examining the effects of no-tillage and cover crops, found CA practices to improve soil physical properties (Nouri et al 2019). After 34 years of NT on one plot and 33 years of CT followed by one year of NT on another plot surface, soil bulk density did not differ between tillage treatments, suggesting the capacity of no-tillage to provide a better compaction resistance. The results showed a 21% increase of macroaggregates under NT compared to CT, while cover crops improved the diameter of aggregates compared to no-cover crop plots. The field research also highlighted improvement of infiltration rate, wet aggregate stability, and moisture content under CA practices, the latter being more obvious in dried periods. Conversely, 15 years of reduced tillage, cover cropping, and rotation on silt loam soil in the subtropical climate resulted in soil penetration resistance not being influenced by residue provided by cover crops but by crop rotation, cover crop, and cash crop rotation interaction. The research also showed that continuous cotton displayed the greatest penetration resistance and that the effect of cover crops on soil force is not consistent and depends on the cash crop cropping system, namely monocropping (Ashworth et al 2020). Nevertheless, rotation with cover crops that have aggressive root systems (sun hemp, pearl millet) was found to improve soil macroporosity in NT systems and reduce soil bulk density, leading to higher yields on clayey soils (Calonego et al 2017; Rigon et al 2020).

The beneficial effects of minimum soil disturbance on soils' compaction show a strong dependence on soil type. Furthermore, its effectiveness seems to be consistent only when completed by other agricultural practices that facilitate organic matter accumulation, namely crop rotation with cover crops and residue incorporation. Alleviating soil compaction is also strongly correlated to the reduction of soil trafficking (Haruna et al 2020), as shown by the long-term empirical study of Ashworth et al (2020), where the machinery traffic associated with crop management in continuous cotton and continuous soybean resulted in the highest soil compaction. A meta-analysis examining the influence of crop rotation on soil's physical health inferred that crop diversification (two or more species) has beneficial effects on bulk density, aggregate stability, porosity, and hydraulic conductivity, especially when legumes are used in the cropping sequence. On the other hand, crop rotation combined with conservation tillage only influence the last three soil physical parameters without affecting bulk density or infiltration rate. Furthermore, the effects in terms of soil compaction were visible for medium-term (5-10 years) empirical studies, while the effects on aggregate stability were visible in over ten years (Iheshiulo et al 2023).

CA practices enabling the improvement of soil physical properties, alleviating compaction, and improving water-stable aggregates (Abid et al 2009; Chen et al 2015; Himmelbauer et al 2012; So et al 2009) also facilitate the exchange of water and nutrients (Adler et al 2020; Andraski et al 2005; Ashworth et al 2016; Piazza et al 2020) in the soil profile. The results of a meta-analysis on the influence of crop residue impact on soil properties and functions (Ranaivoson 2017) showed a reduced effect of crop residue on nutrient supply. There were variable results concerning nitrogen concentration, depending on crop species C:N ratio, phosphorus availability also varied relative to soil pH and residue type. The latter was correlated to the amount of exchangeable potassium. After 37 to 40 years, minimum tillage on loamy Haplic Luvisol in Germany determined higher nitrogen concentrations in the surface soil (0–5 cm) with statistically significant differences compared to conventional tillage. Water aggregate stability was also improved under reduced soil disturbance, with a higher number of water-stable macroaggregates (>0.25 mm) that enhanced the accumulation of soil organic carbon in the surface soil (Jacobs et al 2009). Nutrient cycling can also be influenced by CA practices, through the addition of crop residue. Forty years of continuous corn on silt loam soil, with no tillage and crop residue return to the soil, promoted soil nutrient accumulation and availability, particularly in the topsoil layer (Table 3). Phosphorus (P), potassium (K), and zinc (Zn) contents increased significantly under no-tillage coupled with crop residue retention. Much more P content is positively influenced by residue retention only depending on tillage. The research suggested the removal of crop residue from the surface can alter nutrient cycling in the soil and result in nutrient depletion in the transition layer (18-30 cm), consequently causing plant roots to concentrate at a shallow depth (Kinoshita et al 2017).

Table 3
Reported effects on soil macronutrients (% change vs control) by long-term CA practices, soil texture and depth

Duration	*Soil*	*Multiannual prec. (mm)*	*CA treatment*	*Depth (cm)*	*Macronutrients change %*			*References*
					N	*P*	*K*	
15 yrs.	Silt loam	107, 114^{3}	NT+AWp^{2}	0-15	-0.1^{s}	-8.1^{ns}	-4.2^{ns}	Ashworth et al (2020)
			NT+HV		-	-5.7^{ns}	-0.3^{ns}	
15 yrs.	Typic Xerofluvent, loam soil	864	HLN^{2}	0-10	$+13.4^{s}$	-	-	Mazzoncini et al (2011)
28 yrs.	Fluvisol	948	NT	0-10	-103.4	-	-	Mazzoncini et al (2016)
				10-20	+13.0	-	-	
				20-30	+3.4	-	-	
				0-30	+40.5	-	-	
15 yrs.	Panoche clay loam	210	CC^{2}	0-15	$+16.0^{s}$	-	-	Mitchell et al (2017)
				15-30	$+10.1^{s}$	-	-	
			NT	0-15	$+10.8^{s}$	-	-	
				15-30	$+14.9^{s}$			
12 yrs.	Sandy loam	650	ZT	0-5	-	$+21.5^{*s}$	-	Anil et al (2022)
				5-15	-	$+23.8^{*s}$	-	
12 yrs.	Typic Hapludoll, clay loam	520	RT+CR	0-20	$+2.1^{ns}$			Zhang et al (2015)
			NT+CR		-1.4^{ns}			
40 yrs.	silt loam	-	NT	0-6	-	$+38.7^{s}$	$+14.5^{ns}$	Kinoshita et al (2017)
			NT+CR		-	$+69.1^{s}$	$+128.0^{s}$	
			CT+CR		-	-4.3^{ns}	$+43.2^{ns}$	
			NT	18-30	-	-57.5^{s}	-5.1^{ns}	
			NT+CR		-	-8.6^{ns}	$+61.1^{s}$	
			CT+CR		-	$+1.8^{ns}$	$+56.7^{ns}$	

s/ns – significant/ not significant based on authors analysis, 2 species used as cover crop, 3 two lo-cations with no differences across, AWp – Austrian winter pea, HV – hairy vetch, HLN - high nitrogen supply legume cover crop, NT – no tillage, CC – cover crop mix, ZT – zero tillage, *total organic phosphorus, CR – cash crop residue returned to the soil

Two long-term empirical studies of tillage practices (NT vs CT) in a soybean-corn cropping system with the use of cover crops on Brazilian Oxisols showed improved P accumulation in the subsurface layer (10-20 cm) under NT, while CT effects were mainly restricted to the surface layers (0-10 cm). Tillage effects were most pronounced for the non-labile organic P fraction. On the other hand, results suggested that a type of cover crop researched for its ability to improve soil phosphorus availability (brachiaria) increased total P levels under NT in both soil layers while improving both labile P (5-20%) and organic P (10-25%) at the soil surface (0-10 cm) (Rodrigues et al 2021). A 12-year field experiment with different tillage practices on sandy loam Typic Haplustept in India (semi-arid climate) showed that introducing legumes to maize-based crop rotations contributed to the improvement of loosely bound P, labile P, and other forms of organic P (humic acid-P and alkaline phosphatase). P fertility in surface (0-5 cm) and subsurface

(5-15 cm) soil layers was further improved by tillage, as reduced soil disturbance increased organic P, specifically the zero-tillage flat and permanent beds practices, along with the inclusion of legumes enhanced the availability of phosphorus in the soil (Anil et al 2022) Additionally, other long-term studies highlight that legume cover crops can result in higher soil nitrogen (N)(Ashworth et al 2016) with beneficial effects on soil biota (Ashworth et al 2020).

Different reviews also highlight the beneficial impact of CA on soil physical and chemical properties, namely reducing soil erosion, improving soil biodiversity (Cárceles Rodríguez et al 2022; Palm et al 2014), and water holding capacity (Abdallah et al 2021). The benefits of crop rotation and species diversification extend beyond increasing organic matter and soil nutrient content, thus improving soil quality, and include improving soil biodiversity and microbial activity, reducing the impact of diseases, pests, and weeds (Rietra et al 2022).

Effect of combined CA practices on soil microbial activity. It is widely accepted that CA practices have a beneficial impact on soil microbial communities. Reduced soil disturbance and increased inputs of organic matter boost soil microbial biomass (Hungria et al 2009; Iheshiulo et al 2023; Schmidt et al 2018) and diversity, thus influencing soil biogeochemical processes (Sun et al 2016), which in turn can result in higher soil quality and increased crop productivity.

A long-term (15-year) field trial studying the impact of cover crops and NT practices on soil microbial communities in an arid climate (California Central Valley) showed that CA practices led to positive alterations in terms of microbial abundance and diversity (Schmidt et al 2018). Thus, micro-fauna increased in the surface (0-5 cm) and sub-surface layers (5-15 cm). The highest bacterial numbers were at the surface soil in the NT and cover cropping system and dropped abruptly at lower depths. On the other hand, cover cropping determined a large number of bacteria when conventional tillage was applied, with a gradual distribution through the soil profile. Archaea numbers also showed a positive change correlated to the introduction of cover crops. Although tillage alone did not have a significant effect on the microbial population numbers in the full soil profile (0-30 cm), it significantly increased micro-fauna diversity (Schmidt et al 2018). Another research on the same field site, which studied the fungal communities over a period of 14 years argued that NT influenced the abundance of fungal guilds, creating the condition to favor especially the somatotroph and saprotroph taxa. The same research highlighted the risk of no-tillage increasing the number of plant pathogens (e.g. *Fusarium* sp.), especially in the absence of cover crops. Nevertheless, differences in phototroph numbers were not significant among tillage treatments (Schmidt et al 2019). A meta-analysis of the diversity and community of symbiotrophs (*arbuscular mycorrhizas*) under different agricultural management practices showed an 11% increase in reduced soil disturbance systems completed with cover crops compared to conventional practices (Bowles et al 2017).

After ten years of conservative agricultural management (reduced tillage and crop rotation) applied in China (semi-humid, continental climate) on clay loam soil Typic Hapludoll, the results showed a consistent effect of both tillage and rotation on soil biological activity. NT resulted in higher soil microbial biomass (bacteria and fungi) at the surface soil (0-5 cm) and higher microbial metabolic activity regardless of depth, while crop rotation influenced both the microbial community diversity and its metabolic activity, with the highest rates under the maize-soybean cropping sequence and NT (Sun et al 2016).

Conversely, different soil-tillage and crop-rotation systems tested over 14 years in a subtropical climate on Brazilian Oxisol (clayey texture) resulted in tillage being the main factor influencing soil microbial biomass and activity, while crop rotation had no significant effects either on the microbial population or activity (Hungria et al 2009). Moreover, the results showed that NT favored the development of fungi communities, suggesting a contribution to the improvement of macroaggregate stability. The results of an empirical study conducted in a semi-arid climate on sandy loam soil (Anil et al 2022) showed that the increase in soil biological activities was a combined effect of reduced soil disturbance (zero-tillage or permanent bed practices) and crop rotation, also indicating that different C:N ratio lead to different microbial activity. According to Ashworth et al (2020), using a rotation with cover crops rich in nitrogen to enhance crop diversity favors soil biota, compared to high C:N ratio species, favoring nutrient availability for subsequent crops. A long-term field trial (23 years) on Brazilian clayey Oxisol showed higher microbial biomass and a lower metabolic quotient under the CA system using NT and winter cover crops, suggesting a more efficient microbiological activity and a stable soil system (Balota et al 2014). Additionally, a meta-analysis from 62 studies and 139 observations also showed higher microbial biomass and enzyme activity under no-tillage practices, completed by a lower metabolic quotient. However, long-term empirical studies considered in the meta-analysis did not result in significant differences in terms of metabolic quotient between conservation and conventional tillage (Zuber et al 2016). In contrast, a critical review of 60 experiments showed a positive effect of cover crops on soil microbial parameters. The impact of cover cropping was lower with conservation tillage compared to conventional tillage. Furthermore, the impact of cover crops in enhancing soil biota was more pronounced under arid conditions and with mechanical termination of the cover crop (Kim et al 2020). Conversely, a global meta-analysis suggested that no-tillage with residue retention was a promising conservation strategy to improve soil microbial biomass and quotient in sub humid climates and loam soils (Li et al 2018).

Conservation agriculture and crop yields. Healthy soils are the source of higher yields when favorable climate conditions are met, on the other hand, they ensure crop resilience in less favorable growing conditions (Congreves et al 2015). In terms of CA management systems, crop rotations, and cover crops are practices positively correlated to higher cash crop yields, while conservation tillage negatively impacts yields, although it enhances soils microbiological activity, therefore facilitating nutrient cycles nutrient cycles (Pearsons et al 2022; Rietra et al 2022). Nevertheless, enhanced cash crop productivity (corn and winter wheat) was attributed to cover crop integrations and use of N fertilizer (Chahal et al 2021), while N availability and mineralization were considered the limiting factor of the corn yield in a reduced tillage-based corn-soybean rotation (Hungria et al 2009).

A global critical review (678 studies) showed a 5.1% yield decrease under NT, varying from a 12% decrease without N fertilizer to a 4% diminishing with mineral nitrogen fertilization. The same meta-analysis revealed a higher negative impact of no-tillage on corn and rice yields (-7.6% and -7.5%), while wheat yields were less affected (-2.6%). Interestingly, the impact of conservation tillage on different cereals (triticale, rye, oat, barley, sorghum, and millet) and legumes was lower for empirical trials lasting over 3 to 10 years, much more oilseeds and cotton yields were not affected by no-till. The results also expressed how the negative impact of no-till might be limited in humid climates or by combining it with other conservation agriculture principles (crop rotation and residue retention)(Pittelkow et al 2015). A systematic review analyzing 49 meta-analyses in the scope of conservation agriculture's impact on yield improvements and sustainable land usage also found that no-tillage combined with residue retention results in yield variation ranging from -1% to 10.2% while NT alone was associate with 8% to 10% yield decline (Xiao et al 2021). Similar effects were found by a meta-analysis of conservation agriculture field trials conducted in China. Crop residues and tillage (conventional or no-tillage) increased yields by up to 6.3%, while NT had no statistically significant effect (Zheng et al 2014).

Several empirical studies also correlate soil residue resulted for CA practices to yield growths or reduced variability of yields compared to conventional practices. This can be achieved either by incorporating main crops residue or by using cover crops residues. Long-term research (12 years) in China, on clay loam soil in a temperate continental climate, found higher corn yields under minimum soil disturbance (Table 4) completed with residue incorporation (Zhang et al 2015). The findings were attributed to higher soil moisture. The study also found that the effect of minimum soil disturbance coupled with residue retention is more evident in low-yielding years, inferring that CA management practices are tools to manage the impact of adverse climatic condition on yield variability. Similarly, six cropping systems evaluated under no-tillage for 15 years in Tennessee on Loring silt loam soil found corn-soybean rotation to yield the highest, closely related to soil hydro-physical properties and macro-aggregates stability (Lee et al 2019). A drought-inducing field trial conducted in a CA system (36 years, rotation X tillage) in Canada (silt loam, in humid continental climate – 946 mm annual precipitations) found that integrating cover crops and small cereal grains in the corn-soybean rotation improved corn drought-related yield losses. Conservation tillage (no-tillage) had no impact on yield drought resistance, but the results were strongly correlated to soil organic matter (Renwick et al 2021). Additionally, Xu et al (2019), found crop straw return to reduce yield variability of a wheat-maize rotation under subsoiling tillage, after 11 years of research on brown loam soil in a semi-humid monsoon climate. According to authors these conservation agriculture practices increased the SOC content, leading to the positive effect on yield (Xu et al 2019). Two long-term Canadian research (21 years and 36 years) on soil health indicators and crop yields linked the positive effects of no-tillage and crop rotation on wheat, corn, soybean, and oat yield to the accumulation of SOC (Chahal et al 2021). Supposedly, crop rotation returned more residue to the soil, and succeeding opposite C:N ratio plants (corn-soybean) ensured an equilibrium in the mineralization process. Thus, crop diversity positively influenced soil health, supporting the hypothesis of increasing crop productivity. Similar effects were found by a meta-analysis on soil organic matter, and maize and wheat yields, linking higher concentrations of SOC to yield increments (Oldfield et al 2019).

Table 4

Reported effects on yields (% change vs control) by long-term CA practices, soil texture and depth

Duration	*Soil*	*Multiannual prec. (mm)*	*CA treatment*	*Cash crop*	*Yield change %*	*References*
12 yrs.	Silt loam	107, 114^3	NT+Monocroping+AWp^2	Corn	-1.7^{ns}	Ashworth et al (2016)
			NT + C-S-C-S+AWp^2		$+8.7^{ns}$	
			NT + T-C-T-C+AWp^2		-4.1^{ns}	
			NT+Monocroping+HVp^2		$+0.0^{ns}$	
			NT + C-S-C-S+HVp^2		$+2.0^{ns}$	
			NT + T-C-T-C+HVp^2		$+11.8^{s}$	
			NT + Monocroping+W^2		-7.9^{ns}	
			NT + C-S-C-S+W^2		-11.7^{s}	
			NT + T-C-T-C+W^2		$+3.2^{ns}$	
21 yrs.	Orthic Humic Gleysol, clay loam	895	NT	Corn	$+8.8^{s}$	Chahal et al (2021)
				Soybean	$+25.6^{s}$	
			C-S	Corn	-5.2^{ns}	
			C-S-W		$+3.6^{ns}$	
			C-S-W-RC^2		$+13.2^{s}$	
36 yrs.	Gleyed Melanic Brunisol, silt loam	-	C-C-O-RC^2-B-RC^2	Corn	$+26.9^{s}$	
			C-C-O-B		-11.1^{s}	
			C-C-S-W		$+1.0^{s}$	
			C-C-S-W-RC^2		-5.0^{ns}	
			C-C-S-S		-11.1^{ns}	
			C-C-A-A		$+33.2^{s}$	
34 yrs.	Lexington silt loam	1350	NT	Cotton	$+12.1^{s}$	Nouri et al (2019)
11 yrs.	Brown	697	NT	Wheat	$+5.6^{s}$	Xu et al

Duration	*Soil*	*Multiannual prec. (mm)*	*CA treatment*	*Cash crop*	*Yield change %*	*References*
	loam		SB		+12.7 ^{s}	(2019)
			CT+CR		+5.6 ^{s}	
			NT+CR		+15.5 ^{s}	
			SB+CR		+18.3 ^{s}	
			NT		+6.7 ^{s}	
			SB		+19.1^{s}	
			CT+CR	Corn	+4.5 ^{s}	
			NT+CR		+25.8 ^{s}	
			SB+CR		+28.1 ^{s}	
12 yrs.	Typic Hapludoll, clay loam	520	RT+CR	Corn	+4.8 ^{s}	Zhang et al (2015)
			NT+CR		+4.4 ^{s}	
12 yrs.	Typic Fragiudalf, silt loam	644	CT+HV^{2}/R^{2}	Soybean	-0.5^{ns}	Olson et al (2014)
			CP		+1.4^{ns}	
			CP+HV^{2}/R^{2}		-4.7^{ns}	
			NT		+8.9^{ns}	
			NT+HV^{2}/R^{2}		+4.2^{ns}	
			CT+HV^{2}/R^{2}	Corn	-1.2 ^{ns}	
			CP		+0.9 ^{ns}	
			CP+HV^{2}/R^{2}		-2.3 ^{ns}	
			NT		-3.6 ^{ns}	
			NT+HV^{2}/R^{2}		-6.8 ^{ns}	

s s/ns – significant/ not significant based on authors' analysis, 1 classic 3 years intercropping, 2 species used as cover crop, 3 two locations with no differences across, C – corn, T - cotton, S – soy-bean, A – alfalfa, O – oat, B – Barley, AWp – Austrian winter pea, HV – hairy vetch, W- wheat, NT – no tillage, RC – red clover, SB – subsoiling, CR – cash crop residue returned to the soil, CP – chisel plow tillage, HV/R – Hairy vetch/ cereal rye.

Conversely, after 15 years of CA management under the Mediterranean climate, the above ground biomass of the main crop was higher under conventional tillage completed by rotation with a high nitrogen supply legume cover crop, but not linked to higher SOC levels. The latter was attributed to lower mineralization under NT (Mazzoncini et al 2011). Similarly, a 12-year research on silt loam soil in southern Illinois found similar corn and soybean yields among conventional (plowing) and conservation tillage (chisel and NT). The results showed that while cover crops increased SOC stock, this improvement did not reflect on yields (Olson et al 2014). Figure 1 supports the conclusions of the aforementioned empirical studies with a weak direct relationship (r^2= 0.199) between changes in SOC (%) and yield variation (%) under different CA practices. Cropping diversity under no-tillage promoted higher corn yield in a humid subtropical climate according to the results of a 12 years field study (Ashworth et al 2016). Nevertheless, authors highlighted a low production variability under CA practices, with equivalent yields across rotations and cover crops compared to the continuous corn treatment. The findings are attributed to N dynamic under different C:N ratio residue influencing nutrients availability.

Similar arguments supported the corn yield increase under dry temperate climates and irrigated sandy soil in Germany (Huynh et al 2019). Nevertheless, the results showed higher yield with crop rotation than continuous corn, and although in the first two years, no-tillage yield was equivalent to conventional tillage. In the long run the latter ensured higher yields.

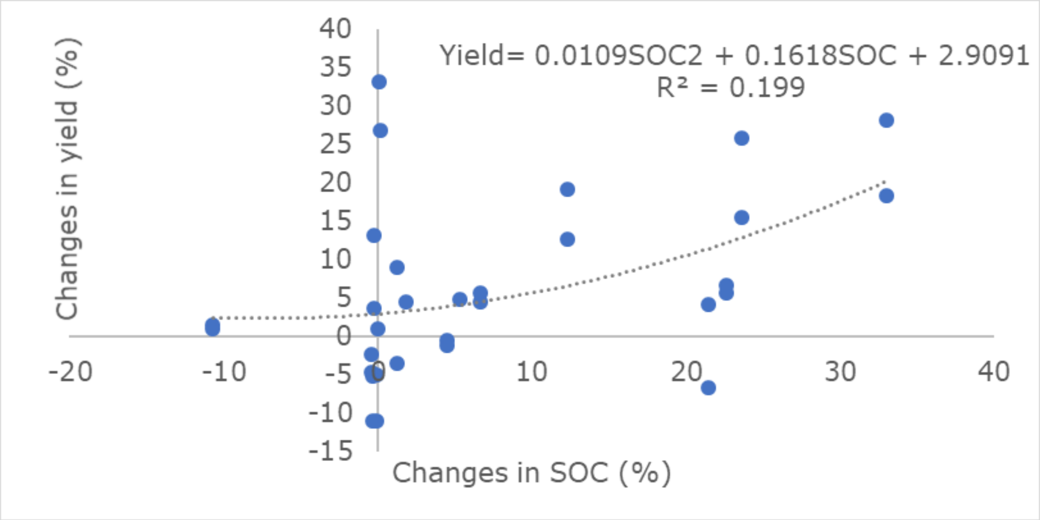

Figure 1. Yield variability in relation to SOC, based on changes (%) from field trials reported in tables 1 and 4.

Long-term research (23 years) in Italy on silt loam soil resulted in a wheat yield decrease under minimum tillage, while soybean yield was not variable under different tillage practices (Piazza et al 2020). Another long-term research (15 years) in a semi-arid climate with irrigation found that NT coupled with cover crops did not affect cotton yield. Yield variability was associated with main crop establishment difficulties. The results also showed that sorghum with no-tillage and cover crops can yield similarly to conventional tillage (Mitchell et al 2017). A 34 years research in the sub humid climate of South-eastern USA, examining the effects of no-tillage and cover crops on Lexington silt loam soil, found CA practices to improve soil quality and increase cotton yield by 12%. Tillage had a consistent effect on cotton yield regardless of the type of cover crops (Nouri et al 2019). In contrast, long-term research (47 years) on orthic luvisol in France showed that the use of cover crops held the main effect in improving maize yield under no-tillage in a maize-winter wheat rotation. According to the results, tillage impact depended on the main crop. Maize yields were equivalent for conventional and conservation tillage, while sugar beet and spring pea yielded higher under conventional tillage (Labreuche et al 2018). Similarly, a 17-year field trial involving rotation of soybean with triticale/ sunflower and different cover crops (pearl millet, forage sorghum, sun hemp) resulted in higher yields compared to the fallow treatment (chiseled every six years). Sun hemp used as a cover crop generated the highest yield growth in soybean, and overall, cover crops were a better option for long-term yields on clay Typic Rhodudalf in the mesothermal climate of Brazil (Calonego et al 2017).

Although the causal relationship between crop yield and CA practices is complex and context-dependent, minimum soil disturbance in the absence of additional conservation practices that favor residue retention might lead to lower yield in more scenarios than when coupled with agricultural practices enhancing soil organic matter. A global meta-analysis of over 4400 paired observations on yield variability under CA tillage practices found lower yields under NT compared to NT coupled with crop rotation and cover crops (Su et al 2021a). The same critical review showed yield responding better to NT under dry conditions. Additionally, Chahal & Eerd (2023) analysing over 670 observations from 63 studies in the scope of yield variability showed that cover cropping might contribute to yield improvements both under no-tillage and conventional tillage systems in temperate climates. Best practices resulting in higher yields involve incorporating cover crops residues and using legume cover crops species (Chahal Eerd 2023). Likewise, a meta-analysis on the variability of corn yield under CA practices emphasized a more substantial increase in the yield determined by winter legume cover crops under NT (30%) compared to plowing (15%) (Marcillo et al 2017). Similarly, Bourgeois et al (2022) found legume and mixed cover crops to have the highest impact on corn and small grains cereal yields, by analyzing 86 studies on humid temperate climates. The meta-analysis also highlighted a decline in grass cover crop's negative effect with the increase of precipitation and the potential competition for water cover crops pose to the subsequent crop, especially under drier conditions. Adoption of cover crops remains controversial despite reported benefits on yields when associated with reduced tillage. Cover crops' potentials on improving soil properties was documented in numerous studies (Abdalla et al 2019; Adetunji et al 2020; Ogilvie et al 2021; Quintarelli et al 2022; Van Eerd et al 2023), but their competition with the subsequent crop for water and nutrient and cost associate to their establishment and management limit their adoption.

When yield performance was attributed to unfavorable soil and climate conditions or poor agricultural systems, low costs and increased returns for CA practices were used as an argument to support CA. The overall conservation agriculture concept is often associated to cost savings (Basch et al 2015; Kertész et al 2014). However, a small body of relevant studies addressed the economics of overall CA practices (Andersson et al 2014; Nordblom et al 2023; Pannell et al 2014) and results are strongly heterogeneous. While the adoption of no-tillage or reduced tillage often translates to cost economies, particularly due lower fuel consumption (Giller et al 2015; Thomas et al 2007), cover crops were reported to have a negative economic impact (Holman et al 2018). Thus, cover crops usage was not consider viable in the absence of subsidies (Acharya et al 2019). A long-term study (29 years) on the economic viability of using NT and cover crops in a cotton cropping system showed that cover crops cost was not offset by additional yields, and net returns were higher in the absence of cover crops regardless of the tillage system (Zhou et al 2017). Labreuche et al (2018) found a net margin drop of up to 30 euro/ha annually when using cover crops in a maize-wheat cropping system. Therefore, further research comparing the potential tillage related savings to additionally costs associated the generation of residues, especially when using cover crops, should be considered especially over an extend time to support results viability. The lack of a financial argument corroborated with yield variability under CA practices hinder CA recommendation and adoption

Conclusions. Numerous scientific researches have documented the influence of CA practices on soil health parameters and, subsequently, on crop production. Several beneficial effects, such as improving soil organic matter, nutrient cycles, microbial activity, aggregate stability, and reducing soil compaction, should lead to more productive soils. Despite the positive impact on soil parameters, and although benefits are context-dependent, the influences of CA practices on cash crops (main crops) yield remained of high variability. Therefore, inconsistencies in the results became detrimental in promoting these practices as a valid alternative to current intensive agricultural systems. The lead motivators of farmers in adopting CA are the beneficial effects on soil properties (Casagrande et al 2016; Knowler et al 2007; Lahmar et al 2010) and the valuable returns in terms of improved yields or cost economies(Mitchell et al 2017; Vincent-Caboud et al 2017). The findings from this review of long-term empirical studies and meta-analysis strongly support a better understanding of the long-term effects of Conservation Agriculture (CA) on soil parameters. The implementation of CA practices has shown positive effects on soil organic carbon (SOC) levels, primarily in the surface layer (0-5 cm) and sporadically in the subsurface (5-10 cm). However, the differences in SOC between CA and conventional tillage were negligible in the lower depths of the soil profile (0-30/0-60 cm). Additionally, other beneficial effects on soil physical (e.g., bulk density), chemical (e.g., nutrients), and biological properties were predominantly observed in the surface layers. While some improvements in soil parameters, such as SOC and aggregate stability, were attributed to tillage (Congreves et al 2017; Jacobs et al 2009; Mary et al 2020; Mitchell et al 2017), the effectiveness of minimum soil disturbance was enhanced when combined with crop rotation, with or without cover crops (Ashworth et al 2016; Chahal et al 2021; Jagadamma et al 2019; Kinoshita et al 2017; Mazzoncini et al 2011). This combination facilitated residue incorporation and organic matter accumulation.

It is important to note that the impact of CA practices on crop yields remains strongly associated with site-specific conditions. Two patterns emerged from long-term field trials and meta-analysis: (1) different combinations of CA practices supported yield increments in favorable climate and soil conditions, with crop-dependent effects, and (2) combining minimum soil disturbance with residue incorporation proved to be a sustainable and cost-effective agricultural practice, reducing yield variability, enhancing drought resilience, and promoting agri-environmental sustainability. However, the absence of crop residue in no-tillage or reduced tillage systems tended to have a negative impact on yield, although some studies found benefits in dry conditions (Nordblom et al 2023; Pittelkow et al 2015; Su et al 2021a).

The review of long-term studies shows that there is a heterogenous pool of researches comparing different CA practices to conventional techniques, hence an approach focusing on optimizing CA practices on the long-term to the full extent of its benefits, would help drive innovation in this field. Further research is needed to evaluate the impact of CA practices on the subsoil layer, especially by incorporating perennial crops or deep-rooting species into the rotation. Additionally, exploring the dynamics of soil biota and its interaction with cropping diversification could provide valuable insights. Further studies should closely evaluate economic-related aspects of combining different CA practices, considering, for instance, how potential cost savings associated with tillage might be diminished by expense increases associated to cover crops to address farmers concerns in terms of economic returns.

The adoption of CA is not a universal approach, but testing several management systems that translate its principles under several site (farm) specific conditions (soil, climate, and long-term sustainability objectives), might lead to finding those strategies that effectively address the unique challenges faced by farmers, ultimately paving the way for the successful and widespread adoption of CA.

Acknowledgements. This research was funded by Syngenta Crop Protection AG and University of Agronomic Science and Veterinary Medicine of Bucharest through Moara Domnească Agricultural Research-Development Didactic Station.

Conflict of interest. The authors declare no conflict of interest.

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Received: 02 June 2024. Accepted: 01 August 2024. Published online: 16 August 2024.

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How to cite this article:
Radu M., Bolohan C., Mihalașcu C., Măruțescu A., Newbert M., Vasileiadis V., 2024 Conservation agriculture impact on soil and crop productivity: a review of long-term field trials. AAB Bioflux 16(1):1-26.