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Review

Conservation Agriculture Effects on Soil Water Holding Capacity and Water-Saving Varied with Management Practices and Agroecological Conditions: A Review

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Abstract: Improving soil water holding capacity (WHC) through conservation agriculture (CA)-practices, i.e., minimum mechanical soil disturbance, crop diversification, and soil mulch cover/crop residue retention, could buffer soil resilience against climate change. CA-practices could increase soil organic carbon (SOC) and alter pore size distribution (PSD); thus, they could improve soil WHC. This paper aims to review to what extent CA-practices can influence soil WHC and water-availability through SOC build-up and the change of the PSD. In general, the sequestered SOC due to the adoption of CA does not translate into a significant increase in soil WHC, because the increase in SOC is limited to the top 5–10 cm, which limits the capacity of SOC to increase the WHC of the whole soil profile. The effect of CA-practices on PSD had a slight effect on soil WHC, because long-term adoption of CA-practices increases macro- and bio-porosity at the expense of the water-holding pores. However, a positive effect of CA-practices on water-saving and availability has been widely reported. Researchers attributed this positive effect to the increase in water infiltration and reduction in evaporation from the soil surface (due to mulching crop residue). In conclusion, the benefits of CA in the SOC and soil WHC requires considering the whole soil profile, not only the top soil layer. The positive effect of CA on water-saving is attributed to increasing water infiltration and reducing evaporation from the soil surface. CA-practices' effects are more evident in arid and semi-arid regions; therefore, arable-lands in Sub-Sahara Africa, Australia, and South-Asia are expected to benefit more. This review enhances our understanding of the role of SOC and its quantitative effect in increasing water availability and soil resilience to climate change.

Keywords: soil organic carbon; water holding capacity; pore size distribution; infiltration rate; soil water storage; aggregates stability

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1. Introduction

Matching food production with the rapid population growth using sustainable and environmentally friendly approaches represents a big challenge, particularly under the changing climate [1–6]. Water scarcity is a major concern for the next decades [7–10]. Unfortunately, the problem of water scarcity is expected to escalate due to rapid population growth and climate change [11–13]. Climate change models predict more excessive heat waves, more intense and frequent-drought waves, and a higher frequency of intensive rainfall [14–18]. The projected increase in rainfall variability, on one hand, and evapotranspiration, on the other hand, are foreseen to decrease water availability and increase flood risk and drought frequency; therefore, crop productivity and yield stability are adversely affected [12,19–21]. However, the consequences of climate change could be mitigated by enhancing soil health and, thus, its resilience/adaptability to drought waves and high rainfall intensities [17,18,22–28].

Soil water holding capacity (WHC; the total amount of water that a soil can retain after the excess water has been drained out) is a key to crop production that contributes to the alleviation of climate change impacts by buffering yields against weather variability [18,23,28–37]. Improvement in soil WHC results in enhancing soil resilience to the increasing climate variability and also helps the agro-ecosystem's adaptation to the occurrence of extreme events, e.g., intensive rain and drought waves [17,23,25,27,32,33,38,39]. Increased soil WHC is mostly associated with higher infiltration rates and lower runoff; thus it could decrease the potential of soil erosion, in particular during intense rain events [17,18,24,27,40–44]. However, soils with low WHC lose a significant portion of irrigation and/or rainwater by deep percolation, thus leaching nutrients from the root zone, leading to inefficient use of resources and adverse environmental problems and a decrease economic outcomes [33,45,46]. Therefore, soil WHC is one of the most important soil properties influencing resource use efficiency, nutrient cycling, crop productivity, yield stability, and environmental quality [47,48]. Williams et al. [18] recorded data on weather and soil factors from four US states (Illinois, Michigan, Minnesota, and Pennsylvania) throughout the period from 2000 to 2014 to quantify their impact on yield stability. They concluded that the WHC of the soil significantly affected yield volatility in the four states. Therefore, there is an urgent need for increasing soil WHC using sustainable and environmentally friendly approaches.

It is widely accepted that both soil WHC and available water holding capacity (AWHC; the amount of water that a plant can uptake) could be improved by increasing soil organic matter (SOM) [2,17,28,29]. Interestingly, the adoption of conservation agriculture (CA)-practices could increase SOM and alter pore size distribution (PSD) [24,49–51]. Therefore, CA-based management practices could positively affect WHC and AWHC of the soil both directly, by increasing SOM due to its hydrophilic properties, and indirectly, by altering pores connectivity and PSD [2,25,37,52–55]. CA comprises principles of minimum mechanical soil disturbance, soil mulch cover/crop residue retention (CRR), and crop diversification [12,51,56,57]. All the above three CA-principles should be supplemented with best and smart crop management practices for systems sustainability in any agri-food systems (Figure 1).

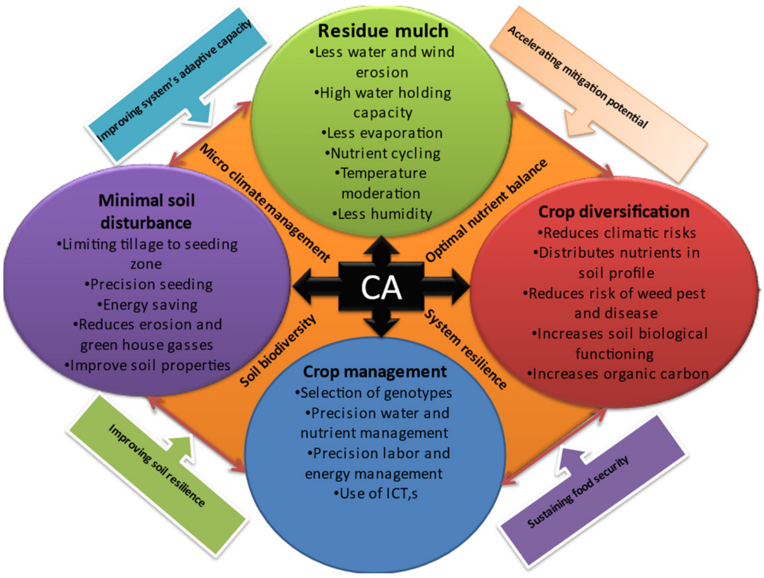

Figure 1. Conservation agriculture-based management practices and their benefits for the agro-ecosystem.

Conservation agriculture and its components have been associated with many benefits, including carbon (C) storing in the soil [22,26,49,53,58–64], improved soil quality [26,57,65–71], decreasing runoff and soil erosion [2,72–75], increasing water productivity [6,52,69,76,77], energy use efficiency [78,79], and, in some cases, higher yield and profitability [6,80–82]. Accordingly, CA has emerged as a promising approach and viable option that could ensure good soil health, yield stability, food security, and buffer crop productivity against climate change [2,17,51,53,61,83]. Promisingly, the results of a recent meta-analysis stated that adopting CA-practices (in South Asia) increased yield, water use efficiency, and net profit by 5.8%, 12.6%, and 25.9%, respectively, while reducing global warming potential by 12–33% [84]. Due to its benefits, the area under CA has expanded four times (from 45 Mha to 180 Mha) in a span of 16 years (from 1999 to 2015), equivalent to 12.5% of the total world's arable land [85]. This trend in area expansion during past decade has been growing at 10.5 Mha per year and the farmers now apply CA on over 200 million hectares in over 100 countries covering 15% of the world annual crop land [51,86]

Earlier reviews considered several topics related to CA-based management practices; however, reviews about the effect of CA-based management practices on the soil WHC and AWHC are lacking. Numerous reviews considered the influence of CA on C sequestration [4,87–90], crop yield [2], environmental quality [87], economics and policies of CA [91–93], weed management [94,95], soil fertility [96], and soil physical and hydraulic properties [97,98]. Reviews focused on the impact of CA-practices on soil physical properties ignored the water retention properties, in particular at field capacity (FC). Additionally, such reviews focused on certain countries, e.g., Chile [99], India [92], and Argentina [100]; specific regions, e.g., Scandinavian [101]; or specific continents, e.g., Europe [73]. Therefore, it is deserving to refine our understanding of if, how, and to what extent CA-practices affect soil WHC and water-saving and availability.

2. Conceptual Framework and Objectives of the Review

Given that soil WHC responds to agronomic management, in this study, we focused on the assessment of the main CA-practices, i.e., minimum soil disturbance, crop diversification, and CRR, that could enhance soil WHC and AWHC. We aimed to review the role of CA-based management practices on soil WHC, AWHC, and water-saving. We hypothesized that CA-based management practices could increase SOC, which, in turn, could increase WHC and AWHC of the soil. Furthermore, CA-based management practices can alter PSD and pore continuity and, thus, WHC of the soil. To do so, as illustrated in Figure 2, first, we reviewed if CA-based management practices increase SOC (Section 3), which, in return directly contributes to soil WHC (Section 4). Subsequently, the potential of CA-based management practices to alter PSD, porosity, and bio-porosity (thus, indirectly soil WHC) (Section 5) was discussed. After that, the change in soil water content (SWC) owing to the changes in soil infiltration capacity and evaporation rate from the soil surface under CA-based management practices (Section 6) were reviewed. Finally, we discussed (Section 7) the role of CA-based management practices and SOC in enhancing water availability due to their effect on some soil physical properties (e.g., aggregate stability, infiltration capacity, and evaporation from the soil surface). The importance of SOM and understanding the SOC-quantitative effect in soil WHC and water availability was also discussed.

The terms of soil WHC, AWHC, or soil water content (SWC) are different. The term soil WHC refers to the maximum amount of water that a soil can hold (the water retained at field capacity). Water content at field capacity (FC) can be determined based on static or dynamic criteria [102]. The widely used approach is the static criteria that determine the soil water content at FC using the suction method (the water content at −10 to −33 kPa) [103] or pedo-transfer functions that depend on soil texture and SOM [104]. However, the dynamic criteria define the FC when drainage is negligible, i.e., time-based concept (soil water content after a designated drainage time) or flux-based concept (soil water content at a designated drainage rate) [105–107]. The AWHC is the net difference between water content at FC and the Permanent wilting point (PWP) [34]. The PWP is taken as the water content at −1500 kPa [103]. Conversely, SWC refers to the amount of water in the soil (i.e., soil water content after rainfall, before irrigation, at sowing, or the end of growth season).

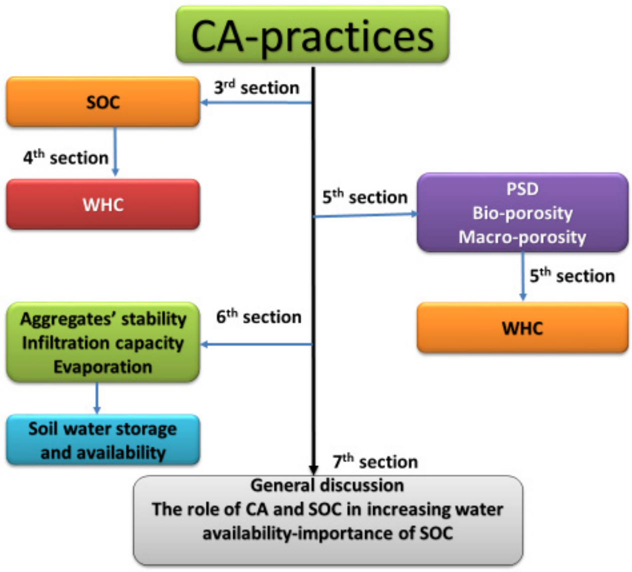

Figure 2. Schematic diagram of the review structure. Where SOC, WHC, and PSD refer to soil organic carbon, water holding capacity, and pore size distribution, respectively.

3. Conservation Agriculture Contribution to SOC

The stability of SOC is crucial for soil health parameters, e.g., fertility, structure, and infiltration [24,108–110]. To conserve and sustain soil health, the buildup of SOC is vital [46,109,110]. The potential of C sequestration in the soil represents a promising two-fold benefit, reducing atmospheric CO_2 and improving soil quality [30,51,64,111,112]. Globally, Zomer et al. [63] reported that arable lands have the potential to sequester about 0.90 to 1.85 Pg C year^{-1}, which corresponds to 26–53% of the target of the "4p1000 Initiative: Soils for Food Security and Climate". In India, Dey et al. [49] reported that adopting CA-based management practices for six years sequestered about 2 Mg C ha^{-1} in the upper 0–15 cm soil layer. However, the influences of CA-based management practices on SOC levels have shown varying results in different soils, climates, and cropping systems [47,48,113–116].

3.1. *Effect of Crop Residue and Crop Rotation on SOC*

Crop residues (CR) are the remaining plant biomass after harvest [2,117] and are considered a renewable resource [69,78]. The soil can store large amounts of OM [63,118]. At the same time, OM in the soil is subjected to microbial degradation, erosion, and leaching. Therefore, the level of SOM in a certain soil is dynamic [4,119]. Consequently, the soil can act as a sink and a source for C at the same time [2,120,121]. Subsequently, it is important to manage the soil to act as a C-sink, not as a C-source. Practices that increase crop biomass while minimizing OM decomposition will result in SOC build-up [12,61]. Theoretically, in comparison to Conv-A, CA-practices will contribute to SOC build-up.

In CA systems, higher CR input can lead to a greater SOC content [89,122,123]. Zhao et al. [61] conducted a meta-analysis to assess changes in SOC under CR retaining through 4910 comparisons from 278 publications across China's croplands, and they concluded that retaining CR increased SOC by 12.3% to 36.8%. Different crops vary in the quantity, quality, and frequency of OM inputs. In this way, within the same system, different crop rotations could impact SOC [26,37,79,124–126]. The decomposition rate of CR (thus, the remaining SOC in the soil) is a function of many factors, including the type of CR [127–131]. It is widely documented that CR with a low C/N ratio accumulates lower SOC due to its high decomposition rate [127,128]. For example, oilseed rape and rye were found to have a higher decomposition rate than wheat straw residues, and thus they accumulated a lower SOC [129]. Similarly, [130] found that CR with a higher concentration of lignin, lipids, and cellulose had lower decomposition rates. Interestingly, a linear relationship was observed between the amount of SOC and the amount of CR retained coming from different crops [132]. Interestingly, increasing crop diversity yields greater and more diverse amounts of CR, thus greater SOC [133–135].

Although it is widely expected that CRR on the soil surface increases SOM, other studies demonstrated an opposite trend, and the general magnitude for this aspect is uncertain due to the contradictory results [4,51,136–140]. Under unfavorable conditions (i.e., reduced soil fertility and/or declined water availability) and in a situation that declines plant growth (cold–humid regions), CA-practices can lead to insufficient plant growth and CR, which could negatively impact SOC [4,51,73,137–139]. Therefore, in areas with low soil fertility, water deficit, or waterlogging, proper site-specific agronomic management (i.e., supplemental irrigation, nutrient application, and providing an efficient drainage network) is critical to ensure sufficient plant establishment and growth, and therefore, a higher potential for SOC buildup.

3.2. Effect of Tillage on SOC

It is well-known that conventional tillage increases SOC losses due to incorporating CR into the soil, thus increasing its exposure to microbial degradation. Moreover, tillage breaks macro-aggregates and exposes protected OM "inside the aggregates" to microbial decay [59,141]. Consequently, reducing soil disturbance can provide a potential to reduce SOC degradation by increasing its protection either inside the macro-aggregates or maintaining it on the soil surface [2,59,66,68,142]. This explanation has been supported by the significant increase in the portion of SOC inside macro-aggregates [26,59], wherein some estimates indicated that the most SOC (more than 75%) was stocked into macro-aggregates [71,143]. Moreover, increasing aggregates' stability (Agg.S) increases water infiltration, and thus, it reduces the potential of SOM loss by erosion, where SOM mostly exists in the top few cms of the soil (more vulnerable to erosion) [48,50,73,138,144–147]. Therefore, Zero-tillage (ZT) has been adopted as a conservationist approach due to its benefits [148,149]. Not only ZT, but also other non-inversion tillage practices, e.g., zonal- and strip-tillage (key components of CA), affect SOC storage. As compared with conventional tillage, sowing under strip-tillage resulted in 62.7–74.7% of CR remaining on the soil surface after wheat and 75.7–82.0% after maize. Such amounts are comparable to those retained on the soil surface under ZT and led to a significant decline in CO_2 emission (98.7–125.9 kg ha^{-1}) [150]. Therefore, compared with conventional tillage, the SOC storage was significantly higher under strip-tillage [116,150–153].

Unexpectedly, compared to Conv-A systems, ZT has been observed to reduce SOC in some cases [73,98,154,155]. Under cold and moist climatic conditions, insufficient CR is produced due to waterlogging and reduced soil temperature. Additionally, when deep-tillage is carried out, CR might be incorporated to a depth where poor aeration can limit its decomposition [154,156]. In China, Du et al. [157] conducted a meta-analysis and concluded that SOC sequestration by ZT should not be amplified. Furthermore, across four US states, which differ in climate, cropping systems, and soil type, Williams et al. [17] assessed the short-term impacts of CA and found that tillage did not affect SOC levels. Furthermore, the results of a review conducted by Soane et al. [73] implied that in northern Europe, ZT did not affect SOC due to reducing soil temperature and waterlogging. Interestingly, Ogle et al. [48] evaluated studies from 178 global sites and concluded that, despite SOC could be higher under ZT under some climatic conditions, however, disparities are very high, and ZT could be considered as an approach for enhancing soil resilience to climate change, not to increase SOC. Recently, in a meta-paper, Liang et al. [113] observed a decline in SOC storage rate owing to ZT in the cold and humid climates of Eastern Canada. However, in the Canadian prairies (semi-arid meadows), ZT consistently and significantly increased SOC storage.

3.3. Combined Effect of CA-Practices on SOC

Several meta-analyses and reviews provided empirical and mechanistic evidence that CA-practices increase SOC near to the soil surface (top 5–10 cm) [48,51,114,120,158–160]. Additionally, numerous studies revealed a positive effect of CA-practices on SOC (Table 1). In Germany, Jacobs et al. [161] found that adopting minimum tillage with CRR increased SOC in the top 5–8 cm soil. In Spain, Pareja-Sánchez et al. [25] found that SOC in the top 15 cm under long-term CA was 21% higher than those under Conv-A. In Northeast China, Guo et al. [59] concluded that ZT with CRR for 17 years increased SOC in the top 5 cm soil layer by 26.0%. In India, after five years of CA, SOC (0–15 cm) increased by 21% [66], 75% [26], and 20% [49]. In Oklahoma, USA, Omara et al. [55] revealed that SOC was increased by 29% and 13% in two different locations due to CA adoption for 18 years.

However, conflicting findings and uncertainty about the role of CA-practices for storing C in soil have been widely reported. Not all studies reported an increase in SOC, even in the topsoil layer; nevertheless, a decline was observed in some cases [48,51,89,157,162–164]. Moreover, CA-practices showed a non-significant annual C sequestration rate [30]. The non-significant effect of CA-practices on SOC has been approved by three novel global meta-analyses, which stated that CA-based management practices had no significant effect on SOC, in particular in cold and cold humid regions [48,51,162].

Several analyses delivered more insights into the aforesaid disputes and indicated that CA-based management practices' contribution to SOC is a function of climate, time since conversion to CA, and soil depth. Regarding the climate, Sun et al. [51] presented a global meta-analysis of ZT-induced changes of SOC and found a significant increase in SOC (in the top few cms) in arid and semi-arid regions, while in cold and cold humid regions, no changes were observed. Similarly, Porwollik et al. [137] reported that in cold, humid, and tropical–humid climates, applying full CA-practices negatively affected SOC levels. In cold-moist environments, low soil temperature and waterlogging may reduce plant growth, thus producing insufficient biomass production and SOC [4,51,73,165]. Similarly, Liang et al. [113] found that ZT decreased the SOC storage rate in the cold and humid climates of Eastern Canada, while in the Canadian prairies, an opposite trend was observed. In this way, most croplands in Australia, China, India, and Sub-Sahara Africa are therefore likely to profit more from CA-based management practices.

Table 1. Examples of soil organic carbon increase due to the adoption of CA-practices (Zero or minimum tillage + crop residue retention, with or without crop rotation).

Country	Climate	Cropping Systems	Soil Texture	Depth (cm)	Duration (Year)	Change (% of Increase)	References
India	Subtropical	Rice-wheat	Clay loam	0–15 15–30	12	40.0 20.0	[49]
China	Continental temperate monsoon	Maize-soybean	Clay loam	0–5	17	26.0	[59]
China	Subtropical monsoon	Rice-wheat	Sandy	0–20	3	28.5	[71]
India	Continental monsoon-Semiarid	Sorghum + cowpea/wheat	Clay loam	0–15	5	21.0%	[66]
India	Semi-arid–sub tropical	Rice-wheat Maize-wheat	Clay loam	0–15	4	67 to 71	[67]
India	Semi-arid	Rice-wheat Maize-wheat	Loam	0–15	6	75 to 80	[26]
India	Semi-arid subtropical	Rice-wheat Maize-wheat	Clay loam	0–15	3	50 to 54	[26]
Oklahoma, USA	Humid subtropical	Winter wheat	Silt loam	0–15	15	13 to 29	[55]
Tunisia	Mediterranean	Wheat	Clay loam	0–30	7	10.5	[166]
Spain	Dry sub humid	Barley	Clayey	0–15	5	15.3	[167]
Spain	Semiarid Mediterranean	Barley	Silt loam	0–30	8	8.7	[168]

Table 1. *Cont.*

Country	Climate	Cropping Systems	Soil Texture	Depth (cm)	Duration (Year)	Change (% of Increase)	References
Germany	Temperate oceanic	Various	Silty loam	0–30	6	11	[169]
Kansas, USA	Semiarid, continental	Various, (cereal based)	Various	0–5	23	6.4 to 40.0	[43]
Spain	Moist Mediterranean	Oats-Triticale	Sandy loam	0–5	8	30.0	[170]
China	Various	Various	Various	0.20	(≥3)	5.1	[157]

As for soil depth, most studies revealed that the significant increase in SOC "if any" occurs only in the 5–10 cm soil depth. However, SOC markedly decreases with depth, implying that CA-practices cannot increase SOC below the soil surface, resulting in an overall negligible change in SOC levels [43,155,157,163,169,171–174]. In a long-term CA study (23 years), McVay et al. [43] measured the changes in SOC in five locations and found that SOC was increased only in the upper 5 cm. Moreover, Baker et al. [175] revealed that the observed increase in SOC in the topsoil (0–30 cm) was coupled with a decline in the subsoil (30–100 cm). Additionally, Du et al. [157] conducted a meta-analysis and concluded that adopting CA-practices led to SOC accumulation only in the upper 20 cm soil layer and depletion in the deeper layers. Furthermore, Blanco-Canqui and Lal [174] measured the effect of long-term CA-practices on SOC across 11 areas in the eastern United States. They observed significantly higher SOC only in five locations, only in the top 10 cm. However, below this depth, an opposite trend was observed. In another study, Blanco-Canqui et al. [155] assessed SOC across three long-term (≥21 years) experiments in the central Great Plains of the USA. However, non-significant differences in SOC between CA and Conv-A systems for the soil profile at any location were observed. SOC was only higher under CA practices in two sites and only for the top 2.5 and 5 cm. The decline in SOC below the surface soil layer was supported by the findings of several meta-papers [48,113,162]. Therefore, the benefits of CA in the SOC requires considering the whole soil profile, not only the top soil layer. Additionally, the time since adapting CA-practices is a vital factor that controls SOC levels. Nair et al. [121], in a review paper, concluded that significant SOC levels (due to CA-practices) could be only obtained in the long-term. Liang et al. [113] revisited the impact of ZT on SOC in Canadian lands and concluded that duration since adopting ZT is a key factor that controls SOC in the soil. SOC levels were also affected by soil fertility management [12]. A previous review paper demonstrated that SOM increased only when CR was retained, and the inputs of N fertilizer exceeded the outputs [88]. Indeed, SOC reversed only when CR inputs were balanced with nutrients' application [136,176]. Excess fertilization proved to enhance SOC level, irrespective of other conditions, i.e., soil type, cropping system, and climate [29,177,178]. For example, the annual applications of farmyard manure at 35 tons ha^{-1} increased SOC by 1.8–4.3% year^{-1} for the whole soil profile in the first 20 years; then, SOC increased by 0.7% for 40–60 years [179]. Similarly, excess long-term application of N, P, and K increased SOC storage by 0.16% year^{-1} [180]. However, the continuous application of such amounts of organic or inorganic fertilizers tend to be unfeasible under real field conditions.

The inconsistency among the findings of storing C in the soil under CA-based management practices can be attributed to the climate conditions [48,51,73,83,89,113,155,181,182], time since conversion to CA [98,113,121,143,183], soil depth [155,157,174], soil type [48,113,184], management [73,162,176], and the use cover crops and intercropping [17]. This inconsistency in results led researchers to a conclusion that CA adoption is not universally applicable for increasing SOC, and the increase is highly constrained in the upper 5–10 cm, while the whole soil profile is not affected [43,155,157,166,174]. Therefore, the large variation in C sequestration designates that the magnitude of change is to be highly site-specific, and its significance must be studied under different climate conditions, cropping systems, soil types, and agro-climatic zones.

4. Soil Organic Matter Contribution to Water Holding Capacity of the Soil

This part of the review aims to address the role of SOM in enhancing the WHC and AWHC of the soil. Due to its hydrophilic nature, OM can hold and retain a sufficient amount of water; thus, it can be an important factor that enhances soil WHC [27,42,46,185]. Therefore, soils with high OM can absorb and hold water during rainfall/irrigation, then release it to plants when the soil starts to dry up [28,29]. Moreover, SOM raises water content at FC more than at PWP, thus positively correlating to AWHC [185,186]. Some reports presented substantial positive effects of SOM on the WHC of the soil. For example, the US Department of Agriculture Natural Resources Conservation Service estimated that for every 1% increase in soil OM, the US cropland could store an amount of water equal to that which flows over Niagara Falls during 150 days [187]. Moreover, adding leaf compost to the soil increased its WHC by 7.5 mm/100-mm [188]. Eden et al. [189] reviewed 17 long-term field experiments that investigated the effects of organic amendments application and reported a significant increase in AWHC. Moebius-clune et al. [36] found a 23% increase in AWHC after 32 years in ZT compared to conv-A and attributed this significant increase to the increase in SOM.

However, numerous reviews and meta-analyses revealed contradictory results and, still, had no clear agreement on the quantitative effect of OM on WHC and AWHC of the soil [42,47,185,186,190,191]. Conversely, others stated that the validity of the reported positive effects of OM on soil WHC is over-estimated and yet to be verified. For example, Minasny and McBratney, [47] conducted a meta-analysis using 60 published studies and analyzed more than 50,000 databases to assess the relations between SOM and water content at saturation, FC, PWP, and AWHC. The results exhibited a non-significant contribution of SOM to WHC and AWHC of the soil. The conclusion of this meta-analysis was reinforced by a review paper that aimed at reevaluating the relative contribution of SOM to WHC of the soil using the National Cooperative Soil Survey Database [190]. The authors found that SOM was weakly correlated with soil WHC ($r = 0.27$; $n = 4783$) for samples between 0% and 8% SOM (most croplands had SOM less than 8%). Moreover, the AWHC was increased by up to 1.5% for each 1% increase in SOM, depending on soil texture in which sandy soils were more affected [190].

Numerous studies observed that the significant increase in SOC did not affect WHC and AWHC of the soil [169,173,192–194]. For example, McVay et al. [43] conducted a long-term study (23 years) over five locations and observed that the increased SOC (in the upper 5 cm) did not result in a greater WHC for the majority of soils. The effect of SOM on WHC and AWHC of the soil is significantly dependent on soil texture, in which the effect "if any" is more evident for coarse-textured soils and non-significant for fine-textured soils [47,190,191]. The results of a global meta-paper by global- [185] and review paper based on Australian publications [186] indicated that most studies revealed an increase in AWHC due to the fact that SOC was greater in sandy soils. Similar results were obtained by Rawls et al. [191] in which they used the soil quality database from pilot studies and the U.S. National Soil Characterization database as affected by long-term management.

5. Effect of CA-Practices on Soil Porosity, Pore Size Distribution, and WHC

Pores in the soil act as a network that control the flow of water and air [195–197]. Soil porosity, pores connectivity, and pore size distribution (PSD) affect soil WHC, infiltration capacity, and oxygen and water availabilities [75,148,198,199]. The adoption of CA-based management practices was found to affect soil porosity, pores connectivity, and PSD, especially in the surface soil layer [98,200]. Such effects vary depending on soil texture, climate, and the time since CA-practices have been implemented [159,198]. A decline in total- and macro-porosity has been widely observed due to adopting short-term CA-based management practices [198,201–204]. In Argentina, Sasal et al. [205] observed that under Conv-A, total porosity was 3.5% higher than that under CA-based management practices in surface soil layer (0–15 cm). In the UK, Mangalassery et al. [149] reported that ZT adoption for seven years decreased porosity by 47% in the upper 10 cm. Short-term CA-based management practices not only reduce total- and macro-porosity, but also increase the fraction of small pores [149,206]. In Italy, Piccoli et al. [207] concluded that the adoption of CA-practices for five years non-significantly affected the macro-porosity, but significantly increased the portion of ultra-micro-porosity. In Brazil, Stone and Silveira, [208] found a higher macro-porosity under the Conv-A system, while a higher portion of micro-porosity was observed after six years of adopting CA-practices. The reduction in macro-and/or total porosity and increase in micro-porosity indicates higher soil compaction in the upper soil layer under short-term CA-based management practices [43,209].

In contrast to the above-mentioned short-term studies, long-time adoption of CA-practices increases total porosity and the fraction of macro-pores [98,148,210,211]. In Brazil, a significant increase in macro-porosity has been observed after 25 years [210] and after 31 years [141], since the adoption of CA-practices. In China, He et al. [212] reported that adopting CA for 16 years increased macro-porosity (>60 μm) by 17.0% in the top 20 cm soil layer. In Brazil, Borges et al. [211] and Galdos et al. [148] demonstrated that the top-soil layer (0–10 cm) under long-term ZT (30 years) was characterized by a higher macro-porosity and pore connectivity than Conv-A. More recently, Guo et al. [59], in Northeast China, found higher pores connectivity in the top 5 cm of the soil, after 17 years of conversion to CA. The importance of the duration since the conversion to CA was approved by the results of a review paper conducted by Blanco-Canqui and Ruis, [98] in which they concluded that short-term (less than five years) adoption of CA-practices showed a little effect on soil porosity, while adopting CA-practices for the long-term (more than 20 years) tends to increase the portion of macropores. Interestingly, under CA-based management practices, soil presents lower values of tortuosity than Conv-A [53,148,213], implying a lower number of disconnected pores that possibly increase soil infiltration capacity [211].

Researchers attributed the increase in macro-porosity and better pore connectivity under long-term adoption of CA-practices to the improved Agg.S, the in-situ decomposed of roots over the years, and the untouched soil macro-fauna, in particular earthworms [4,65,141,148,214]. Under CA, the undisturbed macro-fauna hole the subsoil, leading to an increase in the number of bio-pores, thus increasing macro-porosity [4]. In Germany, Schlüter et al. [215] found that the long-term adoption of ZT (26 years) increased large bio-pores owing to the higher earthworm profusion. In contrast, intensive tillage negatively affects macro-fauna by killing and bringing them closer to the soil surface, thus exposing them to adverse environmental conditions and predators [216,217]. The higher population and diversity of macro-fauna, under CA systems, support this opinion [65,73,214,216,217]. For example, a global meta-analysis observed a greater density and biomass of earthworms with reduced soil disturbance [217].

Despite this, the results of short-term studies (<10 years) on soil porosity give a general trend of porosity reduction; few short-term studies (<10 years) stated that the adoption of CA-practices resulted in higher porosity under ZT than the Conv-A [53]. On the other hand, despite macro-porosity under long-term adoption of CA-practices being well-documented, not all long-term studies followed the same trend, e.g., Lipiec et al. [218] over a long-term study (18 years) in a silt loam soil in Poland and De Moraes et al. [219] over 24 years in clay soil in Southern Brazil. This suggests that the impact of CA-practices on PSD is not only time-dependent, but also site-specific.

After all, the enhanced macro-porosity pores continuity and the increased number of bio-pores likely increase water infiltration, not soil WHC. This conclusion was supported by numerous short- and long-term studies (Table 2) in which soil water retention (SWR) or soil WHC was not affected by CA-practices. In short-term studies, the change in WHC and AWHC of the soil owing to CA-based management practices was non-significant after four cropping cycles [193], six years [169], and eight years [220] of conversion to CA. Likewise, the results of a long-term study (35 years) in eastern Nebraska revealed that the adaption of CA-based management practices exhibited no effect on soil WHC [173]. Furthermore, McVay et al. [43] revealed that despite the increased SOC in the upper 5 cm soil depth, among five sites, only one site had a significantly higher soil WHC. Additionally, after

14 years of converting to CA-based management practices, a non-significant effect on WHC and AWHC of the soil in 0–10 cm depth was observed [192]. In China, no difference in SWR at any given suction was observed, owing to the adoption of ZT [212]. Surprisingly, in a non-irrigated apple orchard in China [54] and clay loam soils in Canada [221,222], CA-based management practices led to a decline in soil WHC.

Table 2. Examples of water holding capacity (WHC) and available water capacity (AWHC) change following the adoption of conservation agriculture practices (zero or minimum tillage + crop residue retention, with or without crop rotation).

Country	Climate	Cropping Systems	Soil Texture	Duration (year)	Depth (cm)	Change in AWHC (%)	Change in WHC (%)	Change in SOC (%)	Reference
India	Subtropical humid	Rice-Wheat	Sandy loam	7	0–15	NA	31	NA *	[223]
Spain	Semiarid Mediter-ranean	Barley	Silt loam	8	0–5 5–15 15–30	48.0 22.0 30.0	30.0 9.6 10.6	16.0 0.05 10.3	[168]
China	Continental monsoon	Wheat	Clay loam	11	0–10	28.0	NA	NA	[224]
Tunisia	Mediterranean	wheat	clay loam	7	0–10 Avg 0–30	16.6 71.4	46.6 38.7	50.0 10.5	[166]
Australia	Humid subtropical	Soybean-Oat	Silt loam	14	0–5 5–10 10–20	19.0 25.0 −5.5	33.3 13.5 −4.7	101.0	[225]
Spain	Moist Mediter-ranean	Oats-Triticale	Sandy loam	8	0–5	35.7	18.5	30.0	[170]
Bangladesh	Subtropical, wet, and humid	Rice-Wheat	Clay loam	4	0–15	11.	NA	26.8	[226]
Austria	Continental to semi-arid	Maize	Loam	10	10–20 50–85	24.7 −11.8	No effect −13.0	No effect No effect	[227]
Spain	Dry sub-humid	Barley	clayey	5	0–15 15–30	13.0 NA	12.5 NA	15.3 −3.7	[167]
Canada	Humid continental	Wheat	Clay loam	24	0–20	−25.0	NA	−9.3	[221]
Canada	Sub-humid, cryoborea	Barley	Clay loam	10	0–2.5 Avg 0–15	−51.0 15.47	−2.54 0.5	NA NA	[222]
Oklahoma, USA	Humid subtropical	Various	Various	2	190	No effect	No effect	NA	[228]
Ohio, USA	Humid subtropical	Maize	Silt loam	14	10	8.0%	9.0%	23.0	[192]
Illinois, USA	Humid continental	Maize-Soybean	Silt loam	8	75	No effect	No effect	NA	[220]
Canada	Humid continental	Maize-Soybean	Clay loam	17	10	No effect	No effect	25.0	[229]
Nebraska, USA	Hot humid continental	Maize	Silty clay loam	35	30	No effect	No effect	11.8 **	[193]
Bangladesh	Subtropical, wet, and humid	Wheat-Mungbean-Rice	Clay loam	4	15	No effect	No effect	32.0	[193]
Germany	Temperate oceanic	Various	Silty loam	6	30	No effect	No effect	11.0	[169]
Kansas, USA	Semiarid, continental	Various, (cereal based)	Various (5 location)	23	5	No effect	No effect	6.4 to 40.0	[43]

* Not available, ** according to [230] (same location, same treatments).

In contrast, very few studies revealed a significant increase in soil WHC and/or AWHC due to CA-based management practices (Table 2). However, such increases were restricted only to the topsoil layer, i.e., 5 cm [170], 10 cm [231], and 15 cm [168,223,226], suggesting that even in these cases, the overall WHC of the soil was non-significantly affected. More interestingly, some studies that reported an increase in WHC and/or AWHC of the surface soil layer (owing to CA-practices) revealed a decline in WHC with depth [166,167,225,227] (Table 2). In brief, most studies that observed an increase in WHC and AWHC of the soil were mostly limited to the top 0–10 cm soil depth. However, as presented in Table 2, several studies revealed that despite the significant increase in SOC in the topsoil, no effect on WHC and AWHC of the soil was observed [43,169,173,192,193].

6. Effects of CA-Practices on Soil Water-Saving

Conservation agriculture practices are drawing increased attention as a promising approach that reduces the water footprint of crops by improving water infiltration, on one hand, and reducing runoff, soil erosion, and evaporation from the soil surface, on the other hand, thus increasing soil water content and water-saving. To understand the impact of CA-practices on water-saving and soil water storage (SWS), understanding the impact of CA-practices on aggregate stability (Agg.S) is of great importance. The non-stable soil aggregates easily slake during irrigation/rainfall, thus limiting water infiltration and increasing the potential of runoff and soil erosion [46,186]. It is widely documented that Conv-A, particularly intensive tillage, contributes to the disaggregation of the top-soil layer [71,141,143,215,218], while the adoption of CA-based management practices maintains and improves aggregates' formation and stability [61,98,159]. Several reviews and meta-analyses concluded that CA-practices increase Agg.S in the top-soil (0–10 cm) [100,232]. For example, Li et al. [233] conducted a meta-analysis and concluded that the stable aggregates in CA systems were 31% greater compared with Conv-A. In China, Song et al. [71] indicated that CA-practices increased large macro-aggregates (>2.0 mm) by 35.18%, small macro-aggregates (2.0–0.25 mm) by 33.52%, and micro-aggregates by 25.10% in the top-soil. Importantly, most studies concluded that the effect of CA-based management practices on Agg.S was evident in the long term [98,159,161].

The positive impact of long-term CA-based management practices on SWS has been documented. The enhanced SWS is ascribed to the additive effect of increased water infiltration, reduced evaporation, and reduced runoff [48,53,66,159,234]. As presented in Table 3, it is well-known that CA-based management practices (especially long-term studies) increase soil infiltration capacity [67,169,170,192,235]. For example, Mhazo et at. [236] conducted a global metanalysis and found that soil losses and the runoff coefficient were 60% and 40% lower under ZT than conventional tillage, respectively. Such a reduction in soil erosion explains the significant increase in water infiltration due to the adoption of ZT. Blanco-Canqui and Ruis [98] found that ZT increased water infiltration by 17% to 86%. Similarly, Alvarez and Steinbach [100] observed that the infiltration rate under CA-practices was twofold that under the Conv-A system. The researchers ascribed the improved infiltration rate to the increased Agg.S of the top-soil layer, higher numbers of bio-pores, enhanced pores continuity, and the increased fraction of macropores [22,53,65,159,214,237].

Moreover, the presence of sufficient CR on the soil surface enhances SWS in two ways, by minimizing water loss by evaporation from the soil surface [52,81,238] and by reducing the negative impacts of raindrops by preventing the deformation of the soil aggregates and erosion [236,239]. In contrast, in Conv-A, when raindrops hit the unprotected soil surface, soil aggregates are destroyed to individual soil particles that clog the pores, impeding water to infiltrate the soil, and hence, it may increase runoff, soil erosion, and SWS. However, in some CA systems, the insufficient CR retention (because of CR removal or poor plant growth, due to factors such as low soil fertility, water deficit, waterlogging, weed, or pest disease) may decline SWS [4,240]. In such situations, Conv-A can increase infiltration rate and SWS more than CA-based management systems [241,242].

Table 3. Examples of the increase in soil infiltration rate (IR) following the adoption of conservation agriculture practices (zero or minimum tillage + crop residue retention, with or without crop rotation).

Country	Climate	Crop	Soil Texture	Duration (year)	Change in IR (%)	References
India	Semi-arid and subtropical	Rice-Wheat	Loam	5	244.0	[67]
China	Continental monsoon	Maize	Clay loam	8	108.0	[243]
China	Continental	Wheat	Silty clay loam	16	300.0	[212]
Germany	Temperate oceanic	Various	Silt	8	231.5	[169]
Australia	Humid subtropical	Soybean-Oat	Silt loam	14	400.0	[169]
Knsasa, USA	Semiarid, continental	Wheat	Silt loam	11	194.0	[244]
China	Subtropical monsoon	Wheat-Corn	Silt loam	9	85.0	[245]
Montana, USA	Subtropical and Subtropical steppe	Spring Wheat	Sandy loam	9	23.0	[246]
Spain	Moist Mediterranean	Oat—Triticale	Sandy loam	8	122.0	[170]
Bangladesh	Subtropical, wet, and humid	Rice-Wheat	Clay loam	4	18.7	[226]
Bangladesh	Subtropical, wet, and humid	Wheat-Mungbean-Rice	Clay loam	4	18.4	[193]
Ohia, USA	Humid subtropical	Maize-Soybean	Silt clay loam	9	245.0	[247]
Ohio, USA	Humid subtropical	Maize	Silt loam	14	46.0	[192]
Canada	Subhumid, cryoborea	Barley	Clay loam	10	14.0	[222]

The higher soil water content under CA-based management practices (Table 4) has been linked to lower soil temperature and lower evaporation from the soil surface [101,238]. Parihar et al. [52] found that CA-practices reduced evaporation by 23%–37% compared to Conv-A. Zhao et al. [61] conducted a meta-analysis to assess changes in SWC due to CR retention across China (through 4910 comparisons from 278 publications) and found that CRR led to an increase in SWC by 5.9% compared with CR removal. Another global meta-analysis concluded that CA-based management practices increased available water by 10.2% compared with Conv-A due to the increased soil infiltration capacity [159]. In the semi-humid to arid loess plateau areas of North China, Su et al. [248] reported that ZT improved soil water storage by 12.62 mm m^{-1} soil depth. Using results from long-term experiments (over 50 years) in a semiarid subtropical region of Australia, CA-based management practices, resulted in greater SWS by 12.7 in the top 1.5 m of the profile compared to Conv-A [62]. They attributed this positive effect to increased soil infiltration and reduced evaporation. In India, the integration of best CA-practices resulted in reductions of 24% in irrigation water due to increased SWS [126]. The increased SWS was confirmed by the higher evapotranspiration in fields under CA than in Conv-A, in which the average water uptake under CA-based management practices was 25% higher than Conv-A [52].

Table 4. Examples of the change in soil water content following the adoption of conservation agricultural practices (zero or minimum tillage + crop residue retention, with or without crop rotation).

Country	Duration (years)	Cropping System	Depth (m)	Increase in SWC%	References
Australia	50	Wheat	1.5	13	[62]
China	10	Wheat	2.0	7	[176]
Spain	19	Barley, Wheat, Canola	1.0	17	[122]
China (meta-analysis)	5–50	Wide range	0.3–1.5	5.9	[61]
India	8	Rice-wheat	0.15	44–54	[223]
India	5	Rice-wheat	0–0.15	8.9	[223]
China	7	Wheat	0–2	25.24 mm	[248]

Under CA-practices, soil moisture could be reserved, therefore enhancing water use efficiency (WUE) and increasing plant tolerance to drought [126]. In a review paper, Alvarez and Steinbach [100] found that the increased SWC under CA in Argentina was enough to meet crop water requirements for a period from 1 to 3 days during the critical flowering period. In India, compared with Conv-A, CA-based management practices increased productivity by 10–17% and profitability by 24–50%, while using less irrigation water by 15–71% [124,126,214,249,250]. An increase of 19% in water productivity, due to adopting CA-practices, was observed in experiments conducted in south Asia across three countries (Bangladesh, India, and Nepal) [251]. Wang et al. [252] conducted a meta-analysis based on the literature published in northwestern and northern China (1950–2018) and concluded that ZT increased WUE of maize by 5.9%, while no effect on WUE of wheat was observed. Such an increase in WUE owing to CA-practices was supported by another two recent meta-analyses that reported an increase in WUE by 14.8% [117] and by 12.6% [84].

The aids of increased SWC owing to CA practices are dependent on the regional climate. Hence, CA-practices are mostly associated with a decreased soil temperature (ST), due to the increased SWC and the mulching effect of CR [51,73,117,139]. The increased SWC and reduced ST showed positive and negative impacts on plant growth, soil health, and the whole agro-ecosystem, according to rainfall, air temperature, and the ratio between the two (humidity index, "HI"; (average rainfall/mean air temperature) [51,73,117]. Generally, in hot, arid, and semiarid regions, the reduced ST can help to improve plant growth [139], microbial populations [253,254], and biomass of earthworms [217]. In contrast, in cold–humid environments, particularly in high-latitude regions, reduced ST due to waterlogging can have disadvantages for soil fauna, early crop establishment, and reduce plant growth; therefore, insufficient biomass for the agro-ecosystem results [5,51,73,137–139]. Such problems are aggravated in clay soil [73]. In Scandinavia, under ZT at sowing, few dry spells could cause poor crop establishment [255]. Conversely, in tropical humid environments, waterlogging especially after heavy rains could lead to a reduction in plant growth [90,256]. The above-mentioned studies were strongly supported by two recent meta-analyses: Lu [117] reported that the highest yield increase was obtained with CA-practices, where CRR was associated with average annual temperatures <10 °C and rainfall ≥800 mm. More interestingly, the meta-analysis conducted by Sun et al. [51] concluded that with an HI < 40 (arid regions and warm regions), the potential benefits of CA-practices are great. Additionally, in semi-arid to humid regions with 40 ≤ HI < 100, CA-practices have the potential to increase SOC, with no yield reduction. However, in regions with HI > 100, cold–humid and tropical humid climates, negative outcomes due to reduced ST and/or waterlogging were observed. Therefore, most soils in northern Europe tend to be negatively affected, while in southern Europe, CA-practices revealed positive impacts [73]. In arid and semi-arid climates, the observed yield increases were mostly attributed to the enhanced SWC and reduced ST under CA systems [51,62,73,139,143,257–262]. Consequently, when adopting CA-practices in cold, wet environments, efficient drainage networks are required to avoid yield losses.

Despite current uncertainties, the results could guide to the adoption of CA-practices in many parts of the world, particularly, in arid regions and regions facing drying trends due to the existing and future climate change [4,48,51,117].

7. Discussion

Despite numerous studies having stated positive effects of CA-based management practices on SOC, others revealed a small or no effect or even a decline. Therefore, there is still no clear agreement on the quantitative effect of CA-practices on SOC. The inconsistent results and large variation in C sequestration due to the adoption of CA-practices are mainly ascribed to the fact that the effects of CA-practices are influenced by climate, time since conversion to CA, soil type, aggregates formation and stability, soil fertility, crop management, and the quantity of OM produced. Therefore, CA adoption is not a universal approach, and the magnitude of change is highly site-specific and very confined to the top 5–10 cm soil surface. Thus, proper site-specific agronomic management is needed. After all, arguments for C sequestering by CA-practices are uncertain (Figure 3).

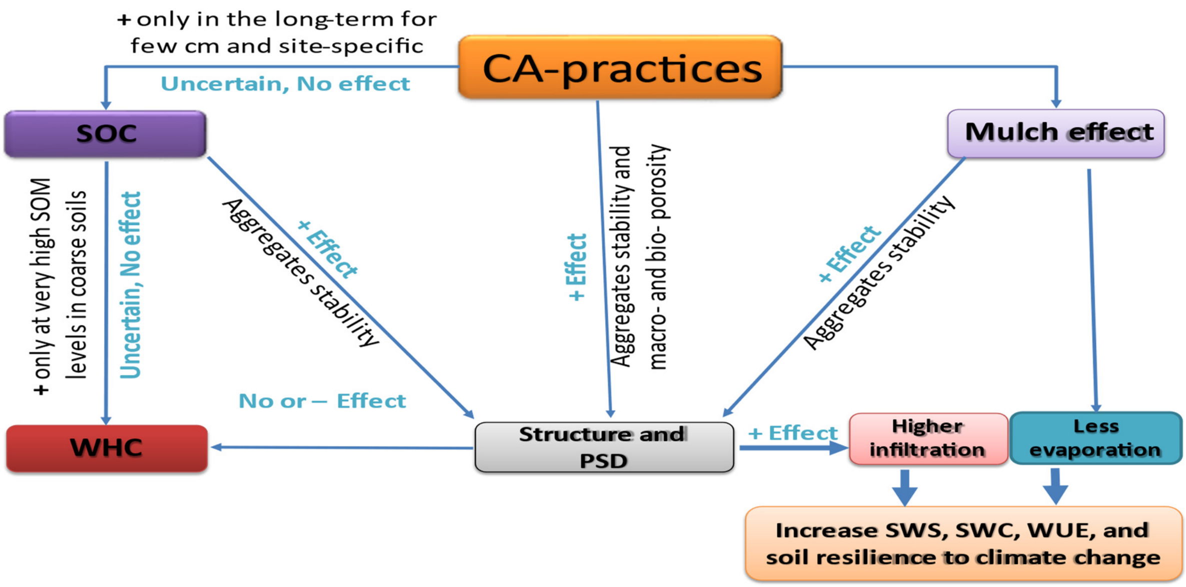

Figure 3. Flowchart of CA-practices contribution to soil organic carbon (SOC), water holding capacity (WHC), soil structure, pore size distribution (PSD), and soil water content (SWC) and storage (SWS).

The effect of CA-practices on soil porosity and PSD was found to be a function of time and the amount of the retained CR, which is affected by several factors. In short-term studies, total and macro-porosity were found to be negatively affected. However, long-term adoption of CA-practices increased total-, macro-, and bio-porosity. The importance of the duration of CA was endorsed by the result of reviews focusing on the effect of CA-practices on soil porosity and SOM, in which the authors concluded that most consistent results were obtained at or above 15 years [263] or 20 years [98] beyond the conversion to CA. Previously, most studies have focused on the agricultural land under CA management for ten years or less, taking into consideration that long-term studies are those of five years after conversion to CA [148]. However, indications propose that the required CA duration to significantly impact soil properties is about 20 to 28 years [98,264,265]. Under long-term CA-practices, the enhanced macro-porosity, at the expense of the water-holding pores, pores continuity, and the increased number of bio-pores, likely increases water infiltration more than WHC (Figure 3).

The contribution of SOM following the adoption of CA-practices to WHC and AWHC of the soil is uncertain and unaccountable, even in the topsoil layer. Meta-analyses and reviews revealed that for each 1% increase in SOM, the AWHC is enhanced by only

1.5 to 2.0 mm/mm [47], 1% [190], to 3, 2.5, and 2 mm 100 mm^{-1} for sandy, loam, and clay soils, respectively [186]. Moreover, the largest increase in AWHC, due to SOM, was found from 0 to 1% SOM, and the increase in AWHC declines with a further increase in SOM content [47]. However, in organic soils, a 1% increase in SOM resulted in only a 0.45% increase in AWHC, confirming that SOM has a negligible effect on retaining water at high SOM levels [190], and there were no considerable returns associated with adding more OM. However, most of the values from the database were within SOM values varying from 0% to 8%, which covers most arable, pasture, and forest lands [190].

The significant increase in WHC and AWHC of the soil owing to SOM could be achieved only at high SOM levels in coarse-textured soils. Such high SOM levels could be reached either by incorporating a large amount of OM [29,46,47,178,185,190,191] (which could not be feasible under field conditions) or by adopting a successful long-term CA [36,189]. For example, an increase in AWHC of 3.7 mm 100 mm^{-1} was obtained by applying 10 Mg ha^{-1} of mulch for an increase in 40 g kg^{-1} of OC [178]. Similarly, Ankenbauer and Loheide [29] found more than a twofold increase in AWHC (from 17 g to 37 mm 100 mm^{-1}) for an increase of 150 g kg^{-1} OC. Unfortunately, the annual C sequestration rates due to adopting best CA-practices do not promote a significant increase in WHC and AWHC of the soil. More importantly, studies of best CA-practices were occasioned with an annual C sequestration rate of 0.1–1.0 MgC ha^{-1} [30], which can be translated to a negligible annual increase of 0.01–0.1 mm/100 mm [47]. Therefore, compared with the reported annual C sequestration rates due to the adoption of CA-practices, the effect on WHC and AWHC of the soil is very slight. This conclusion was supported by numerous studies that reported non-significant changes in water retention at FC, even in the topsoil layer at a higher SOC level, despite the significant increase in SOC of the near soil surface layer [43,169,173,192,193]. After all, quarrels for C sequestering in the soil by adopting CA-practices for enhancing soil WHC is uncertain. This is because, even at a significant SOC level, if obtained, its effect on soil WHC is still small; hence, SOM typically concentrated in the top 5–10 cm of soil surface (2.5 and 3 cm in some cases) limits the capacity of SOM to increase the overall WHC of a soil profile [155,174,266] (Figure 3).

Despite all these inconsistent, controversial and considerably uncertaint findings on the relation between SOM and soil WHC, most studies, empirical relations, reviews, and meta-analyses are consistent with the positive effect of SOM on soil water content and water-saving, even though the effect is limited to the top few cms of coarse-textured soils [47,170,225]. The significant increase in soil water content at saturation due to the presence of SOM can improve the soil resistance to flooding events. In addition, increased water content at saturation is usually accompanied by increased saturated hydraulic conductivity and infiltration capacity [47], thus decreasing the potential of soil erosion.

In this review, we do not underestimate the importance of SOM or propose not to take care of SOM. However, WHC of the soil cannot be increased meaningfully throughout the soil profile, due to increased SOM. Even with the best CA-practices, increasing SOM should still be pursued for improving soil structure, water infiltration, enhancing soil fertility, reducing soil erosion, and decreasing atmospheric CO_2 attenuation. SOM is vital for earthworms to proliferate (food sources), which markedly increase macro and bio-pores and, therefore, infiltration rates. In addition, retaining CR reduces evaporation from the soil surface, thus increasing soil water content (Figure 3). Environmental changes that result in increases in SOM (CA-practices or direct application) will indirectly increase water conservation and availability. In contrast, decreasing SOM will decrease water availability, resulting in adverse consequences for the sustainability of croplands productivity. There is a need to improve our quantitative understanding of the sensitivity/response of soil WHC to SOM to reduce the current level of uncertainty and to provide resource managers with better decision support systems. The benefits of CA-practices could be achieved through CR mulching that reduces evaporation in addition to the increased infiltration that reduces runoff and increases SWC. The increased SWC can reserve soil moisture for a longer time and, therefore, reduce irrigation requirements and enhance water use efficiency and plant tolerance to drought waves. The above-mentioned benefits in SWC and WUE due to CA-practices could be dependent upon the cropping system, climate, and soil type. In arid and semi-arid climates, the observed yield increases mostly were attributed to the enhanced SWS under CA. However, despite current uncertainties, we can conclude that the adoption CA-practices in many parts of the world, particularly in arid and semi-arid regions and growing areas of the world experiencing drying trends due to current and future climate change. In this way, most croplands in China, India Australia, and Sub-Sahara Africa are likely to benefit from CA, including for climate change mitigation.

8. Conclusions

The Main Findings Can Be Highlighted as Follows

The effects of CA-based management practices on SOM are varied, and site-specific, and they depend on the time since adopting CA-practices. The effect of CA-practices is pronounced in arid, semi-arid, and warm regions and is bounded primarily in the upper few cms of the soil under long-term adoption of CA-practices. Therefore, certain site-specific agronomic practices must be considered according to soil type, climate, crop diversity, CR use, water availability, and soil fertility.

The effect of CA-practices on soil WHC is small and governed by soil type and SOC levels under different agro-ecological conditions. The increase in soil WHC due to increasing SOM is pronounced more in coarse-textured soils and can be achieved when a high SOC level is reached by incorporating large amounts of OM. Interestingly, the values of accumulated SOC due to the adoption of best CA-practices do not translate to a significant increase in soil WHC.

Even if a significant level of SOC was achieved due to the adoption of best CA-practices, still the CA-practices' contribution to soil WHC would be small, because the SOC mostly staked to the top 5–10 cm, in addition to the SOC depletion of sub-surface soil horizons. Consequently, the capacity of SOC to increase the overall WHC of a soil profile is small. In conclusion, the benefits of CA in the SOC and soil WHC requires considering the whole soil profile, not only the top soil layer.

Long-term adoption of CA-practices increases Agg.S, the portion of macro-pores, and the number of bio-pores, while it decreases evaporation from the soil surface due to the mulch effect, all of which contribute to enhancing soil resilience to climate change by improving soil infiltration capacity and soil water content, thus decreasing runoff and soil erosion.

CA-based management practices have a limited effect on soil WHC, but when CA-practices enhance SOM, soil structure, porosity, and the infiltration rate increases, and evaporation decreases in return, leading to higher SWC, AWHC, and WUE. In contrast, environmental changes that result in a decrease in SOM will decrease AWHC, resulting in adverse consequences for the sustainability of agricultural productivity.

In cold, cold–humid, and tropical–humid climates, applying CA-practices negatively affects SOC and soil health parameters and productivity due to decreased soil temperature and waterlogging, which can reduce plant growth, which is associated with insufficient biomass production. Therefore, in areas with unfavorable conditions (e.g., low fertility, water deficit, and waterlogging), proper site-specific agronomic management (e.g., supplemental irrigation, nutrient application, and drainage systems) are vital to ensure sufficient plant growth, therefore higher productivity and higher potential to SOC buildup. However, the positive effects of CA-practices are more pronounced in arid and semi-arid regions. In this way, most arable lands across China, India, Australia, Sub-Sahara Africa and other countries are prospective to benefit from CA.

This review enhances our understanding of the role of SOC and its quantitative effect in increasing water availability, WUE, and soil resilience to weather variability. However, unlike many physical soil properties, the changes in soil water retention at field capacity under CA-practices have been less documented. Therefore, further research is needed to assess the effect of CA-practices on the soil WHC in different soil types under different cropping systems and climatic conditions.

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