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Review

Conservation Agriculture as a Sustainable System for Soil Health: A Review

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Abstract: Soil health is a term used to describe the general state or quality of soil, and in an agroecosystem, soil health can be defined as the ability of the soil to respond to agricultural practices in a way that sustainably supports both agricultural production and the provision of other ecosystem services. Conventional agricultural practices cause deterioration in soil quality, increasing its compaction, water erosion, and salinization and decreasing soil organic matter, nutrient content, and soil biodiversity, which negatively influences the productivity and long-term sustainability of the soil. Currently, there are many evidences throughout the world that demonstrate the capability of conservation agriculture (CA) as a sustainable system to overcome these adverse effects on soil health, to avoid soil degradation and to ensure food security. CA has multiple beneficial effects on the physical, chemical, and biological properties of soil. In addition, CA can reduce the negative impacts of conventional agricultural practices on soil health while conserving the production and provision of soil ecosystem services. Today, agricultural development is facing unprecedented challenges, and CA plays a significant role in the sustainability of intensive agriculture. This review will discuss the impact of conservation agricultural practices on soil health and their role in agricultural sustainability.

Keywords: conservation agriculture; indicators; soil health; soil quality; sustainability

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1. Introduction

Soil is the surface material that covers most land, containing inorganic particles and organic matter and supplying structural support to agricultural plants, being thus their source of nutrients and water. Agriculture today faces a double-sided challenge—on the one hand, the urgent need to provide food to a growing population, and on the other hand, to do so in a sustainable way [1], without compromising the provision of ecosystem services by the soil, such as carbon sequestration, nutrient supply, and water cycle regulation.

Sustainable agriculture is a difficult concept to define, since the environmental, social and economic impacts of agriculture are diverse and interact with one another [2]. In general, it can be stated that sustainable crop production systems are those that respect the environment, improve efficiency in the use of resources and promote human well-being [3]. They are those food production practices that integrate ecological, biological, physical and chemical principles, without harming the environment, as opposed to unsuitable agricultural practices [4].

Soil health is the state of the soil in relation to its potential ability to maintain its biological productiveness, strengthen environmental quality, and foster plant and animal health. Sustainable agriculture can be defined as agriculture that can be practiced in a productive and profitable way without affecting the health of the soil [5]. Figure 1 shows the main functions exerted by soil. Today, soil health is threatened all over the world. Some of the main threats to soil are erosion, compaction, salinization, nutrient depletion, pollution, and/or overgrazing [6].

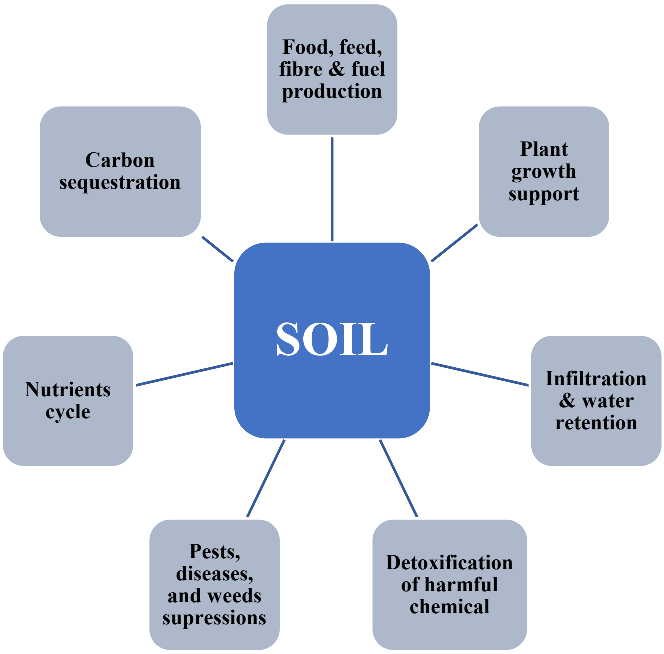

Figure 1. Main functions of soil (Adapted from [7]).

On the other hand, land degradation and deterioration of soil fertility are two of the main causes of the decline in the agricultural productivity of agroecosystems. The intensification of agriculture deteriorates the soil quality, and its negative effects have increased in the past few decades. The aim of conventional agriculture is to produce the highest possible yield of crops by the application of synthetic products, energy inputs, and a number of other industrial products. Biodiversity, soil fertility, and ecosystem health are compromised under conventional systems.

The intensive use of machinery and chemical inputs increases compaction, erosion, and soil salinization and decreases the content of organic matter and soil nutrients, which negatively influences the soil's productivity and long-term sustainability. The degradation of agricultural soil under different cropping systems is a socioeconomic and environmental problem that must be urgently addressed, particularly considering that climate change is expected to have a strong negative impact on food production, as was defined by Smith and Gregory [8]. CA practices are a useful strategy for climate change mitigation and adaptation [9,10]. CA allows slowing down or reducing greenhouse gas emissions and improving carbon sequestration in the soil [11]. The application of CA practices can improve the properties of soil, increasing its resilience to drought, and improving water and nutrient use efficiency. These improvements are essential to maintain the sustainability of agricultural production and mitigate the impacts of climate change on food production [12,13]. To reduce these negative impacts of agricultural systems and guarantee their long-term sustainability, management systems that improve or conserve soil quality are crucial [14]. To this end, agronomic practices of conservation agriculture (CA) are promoted. Figure 2 shows the environmental impacts of conventional agriculture and the benefits of CA on the soil system.

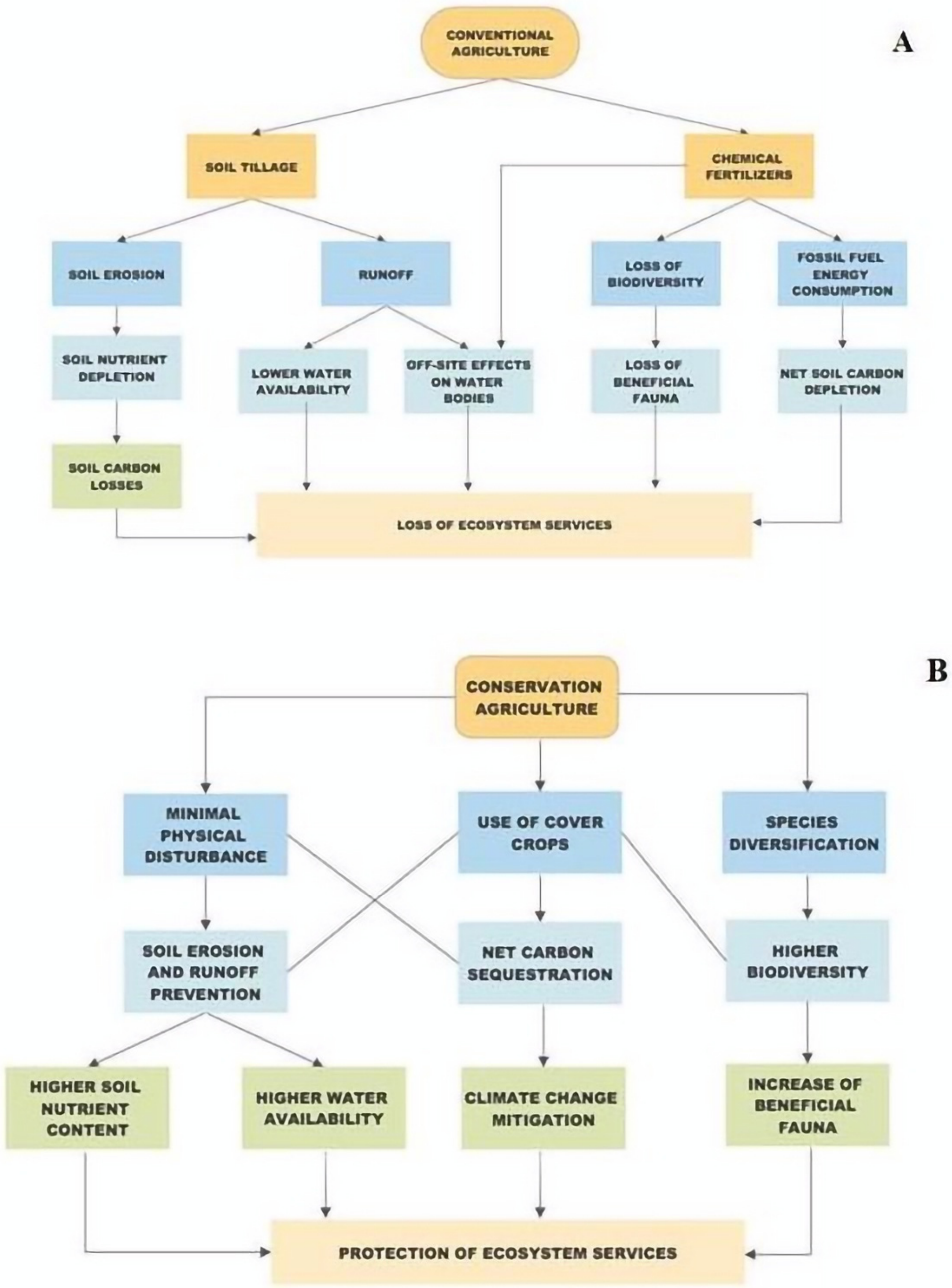

Figure 2. Environmental impacts of conventional agriculture (**A**) and the benefits of conservation agriculture (**B**) on soils.

In this review, we examine and describe advancements in the implementation of conservation agriculture measures as a sustainable system, focusing on their impacts on soil health and its role in supporting the suitable management of land, while fostering food security.

2. Conservation Agriculture

The Food and Agriculture Organization (FAO) defines CA as an agroecosystem management system to ensure food security and improve profits while preserving environmental resources.

Food security, as defined by the United Nations' Committee on World Food Security, means that all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their food preferences and dietary needs for an active and healthy life. Currently almost 800 million people do not have access to enough food, more than 2 billion people experience deficiencies in key micronutrients, and approximately 60% of people in developing countries are food insecure [15]. In addition, it is foreseeable that in the coming decades, the growth of the world population, climate change and environmental impacts will aggravate the problem. The magnitude of the problem globally means that food security is related to all of the Sustainable Development Goals (SDGs) of the United Nations.

Conservation agriculture is an agroecosystem management approach that can be considered as one of the main ways to achieve the sustainability of agriculture, allowing the goal of greater protection while protecting the environment [16]. CA emerged in the 1930s in the USA to combat soil degradation due to water and wind erosion [17]. CA is characterized by the application of three interlinked principles implemented with locally adapted practices, together with other complementary agricultural practices [18]. These three principles are:

(1) Continuous minimum mechanical soil disturbance;
(2) Permanent soil organic cover with crop residues and/or cover crops;
(3) Species diversification through varied crop rotations, sequences, and associations.

The concomitant application of these three individual principles constitutes the classical definition of CA. However, many smallholder farmers cannot apply these three rules at the same time, and CA defined as a fixed package is not often adapted to the particular conditions of small farms. The application separately or in tandem of these components has been shown to have potential benefits, as was reported by many authors [19–21]. However, some of these authors argue that it is necessary to move from the strict definition of CA as a fixed set of three components to talking about conservation practices, which encompass a variety of options for sustainable agricultural intensification [22,23].

CA constitutes the central nucleus of FAO's new sustainable agricultural intensification strategy [24]. According to the FAO, CA is applicable to all "agricultural landscapes and land uses with locally adapted practices", which implies a series of economic, agronomic, and environmental benefits. In this sense, CA is a viable option for the sustainable intensification of agricultural land and obtaining profitable production [25,26].

In 2015/2016, CA was practiced worldwide in 180 M ha (about 12.5% of the total global cropland), an increase of 69% compared to 2008/2009. This growth has been greater in recent years. From 1999 to 2003, the area under CA increased by an average of 8.3 M ha per year [27]. The adoption of CA is not uniform in all regions or among all types of farms. It is generalized in large farms in North America, Australia, and Brazil. In contrast, adoption by smallholder farmers accounts for only 0.3% of the farmland worldwide under CA [28]. Globally, the total CA area is still comparatively small in relation to the total arable land using conventional tillage (CT). As pointed out by Kassam et al. [27], it is expected that large areas of agricultural lands in Asia, Africa, Europe, and Central America will adopt CA in the coming years. The low adoption of CA in developing countries can be attributed in part to the fact that it is a complex system, coupled with insufficient technical knowledge and capacity of farmers. In this context, political and institutional support is essential through incentives for farmers to adopt CA practices and technical support from experts [21].

To increase the implementation of CA techniques and the benefits derived from it, site-specific practices must be designed [22,25,29]. An important constraint is the limited availability in most developing countries of affordable and suitable machinery for no-till seeding, especially for small- and medium-scale farmers [30]. The development and availability of equipment that allows for sufficient germination of crops planted in no-tillage systems, with mulch in the soil, and that can adapt to small- and large-scale farmers should be improved [31]. Therefore, CA is an alternative to enhance productivity and food security, while preserving natural resources and reducing the negative externalities of traditional agricultural practices [32]. Moreover, the CA system can significantly improve the resistance to changing climate conditions in cropping systems [33,34]. In this context, conservation tillage is applied as an alternative to CT in order to alleviate water erosion impacts, reduce production costs, and maintain soil quality [35,36]. The positive effects of minimum tillage on soil quality, environment, and soil water conservation as compared to non-tilled soils in rainfed plantations were highlighted by Jacobs et al. [37] and Busari et al. [38]. Table 1 summarizes the main economic/agronomic and environmental benefits derived from CA practices.

Table 1. Main economic/agronomic and environmental benefits generated by conservation agriculture.

Economic/Agronomic	Environmental
Labor and fuel savings	Lower CO_2 emissions
Cost and time savings	Erosion and surface runoff reductions
Yield gains	Improvement of soil properties
Reduced fertilizer expenditures	Increase in soil biodiversity
Weed control	Increase in microbial activity
Lower irrigation needs	Less pollution of downstream water
Lower risk of pest and disease outbreaks	

Adapted from [31,39].

The cover cropping system as a technique of CA is an essential part of crop rotations in many regions worldwide, dispensing a wide range of benefits and ecosystem services such as N supply and retention [40], weed control [41], soil nematode control [42], water retention [43], and mitigation of nitrate leaching [44]. In addition, in the long term, cover crops can build up soil organic carbon and N [45,46] and lower net N_2O and CO_2 emissions, thus contributing climate change mitigation services [47]. Cover cropping can improve soil organic carbon stocks and potentially promote climate stability and food security, as was reported by Minasny et al. [48]. Similarly, according to Garcia-Tejero et al. [49], who examined Mediterranean rainfed agroecosystems, the use of CA techniques to enhance soil water management and soil carbon storage is vital.

On the other hand, Daryanto et al. [50], in a global quantitative synthesis of ecosystem services from cover crops, reported the suitability of their implementation. Despite the potential benefits of cover crops to improve soil conditions, this measure can add to the complexity of farming operations. According to Clark et al. [51], in the case of hairy vetch (*Vicia villosa* Roth.), which can provide a considerable amount of N demanded by the subsequent crop (maize), a late cover crop harvest is recommended because this allows for higher N accumulation in their biomass and for better synchronization of N release from the decomposing cover crop and maize N uptake [52]. In contrast, the early harvest of the cover crop may be suitable in circumstances where the rainfall amount is low and the depletion of soil moisture reserves by cover crops is a drawback [53].

The CA practices result in soil quality improvement only gradually, and benefits come about only with time. According to Stagnari et al. [54], between 3 to 7 years may be needed for all of the benefits to take hold. Therefore, because long periods are often required before changes in the soil can be detected, studies of CA must be based on long-term research and trials. This transition phase is crucial to ensure the success of the adoption of CA practices. In the initial transition years, problems can arise, such as more difficult weed management [55], lower productivity [56], etc., which can discourage farmers and lead them to abandon these practices.

3. Soil Health

Soil has been receiving increasing political and scientific interest in recent times, given its capability to provide various ecosystem services that contribute to the United Nations Sustainable Development Goals and to the European Union Green Deal [57]. Concepts such as soil health and soil quality are used to refer to this soil capability. The terms soil health and soil quality are often used interchangeably. In fact, the distinction between the two concepts is not clear. According to Laishram et al. [58], soil health refers to a broader concept—the capacity of soil to function as a living system to support plant, animal, and human life. Conversely, soil quality concerns the capacity of a specific kind of soil to sustain a particular use, such as crop production. Bonfante et al. [57] established the following distinction between the two terms: “Soil health is the actual capacity of a particular soil to function, contributing to ecosystem services”, while “soil quality is the inherent capacity of a particular soil to function, contributing to ecosystem services”. Both concepts, soil health and quality, are used to monitor soil status, analyze the influence of soil management on agricultural sustainability, and direct decision making to avoid degradation [4]. Figure 3 summarizes the management principles and the benefits of soil health.

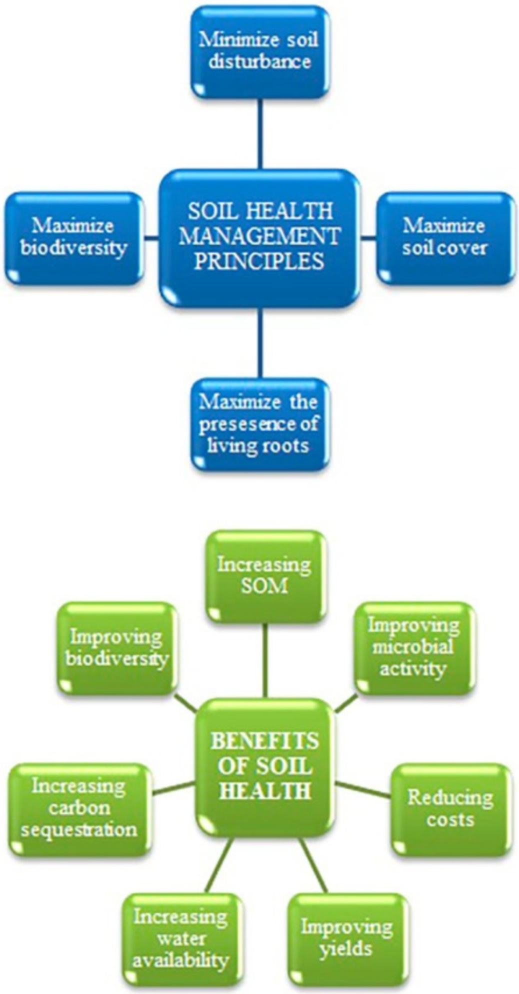

Figure 3. Management principles and benefits of soil health.

Although the concept of soil health emerged in the early 2000s, it is still evolving. It is not an easy concept to define, since soil is an extremely complex ecosystem, as was stated before. There are numerous definitions in the literature. According to Doran and Zeiss [14], soil health is “the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health". The U.S. Department of Agriculture (USDA) [59] defines soil health as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans". Yang et al. [60] defined it as "the capacity of soil to function, within ecosystem boundaries, to sustain crop and animal productivities, maintain or enhance environmental sustainability, and improve human health worldwide".

According to Kibblewhite et al. [5], healthy agricultural soil is "capable of supporting the production of food and fiber, to a level and with a quality sufficient to meet human requirements, together with continued delivery of other ecosystem services that are essential for maintenance of the quality of life for humans and the conservation of biodiversity". According to Wang and Hooks [61], soil health can be defined as having six main characteristics: (i) high biological diversity, (ii) high community stability that can provide resilience and self-recovery to chemical and biological disturbance, (iii) the ability to maintain the integrity of nutrient cycling and energy flow, (iv) the suppression of multiple pests and pathogens, (v) the ability to improve plant health, and (vi) the maintenance of water and air quality.

All of these definitions are conceptual, since they attempt to define what healthy soil is without defining how it is measured. The operational definitions establish a series of key indicators of soil health. It is essential to include indicators of physical, chemical, and biological properties when assessing soil health, as was stated by Bünemann et al. [62]. Ideally, indicators of soil health should be related to relevant soil processes and sensitive to changes in management practices and environmental conditions [60]. There is no universal set of ideal soil characteristics, and their interpretation is always context-dependent [63].

Finally, the concept of soil health can be approached from a "reductionist" or "integrated" point of view. The first is based on estimating the state of the soil using a set of individual indicators of specific soil properties: physical, chemical, and biological. The integrated approach recognizes the complexity of the soil system and the existence of interactions between the different properties and processes of the soil; therefore, soil health is more than simply the sum of a set of specific indicators [5]. According to this integrative approach, the indicators selected to establish soil health must be the result of interactions of the biota with the physicochemical properties of the soil [64]. Thus, healthy soils are crucial for the integrity of agricultural lands to maintain, or recover from perturbations resulting from, agricultural operations, particularly those regarding soil management.

Soil Health Indicators

Knowing and understanding the state of soil health is essential to guarantee the sustainable management of agroecosystems. Soil health is a complex functional concept and cannot be measured directly in the field or laboratory; it can only be inferred indirectly by measuring soil indicators [65]. These indicators are measurable soil parameters that influence soil function and ecosystem services [66].

In general, soil health indicators can be classified as physical, chemical, or biological, although these categories are not always clearly delimited, since there are many soil properties that result from the interaction of multiple processes [67]. Evidently, no single indicator can encompass all processes and parameters of soil health, nor is it feasible (or necessary) to measure all soil attributes. Therefore, it is necessary to select a minimum dataset (MDS) including physical, chemical, and biological parameters of the soil. Establishing a minimal dataset, representative of total data, minimizes costs and efforts in soil health assessment. Table 2 shows an MDS for soil health assessment with the indicators more commonly used.

The desired features of soil health indicators are that they be: (i) easy to measure; (ii) measurable with practical, rapid, and inexpensive measurement methods; (iii) sensitive to variations in management; (iv) relevant to soil ecosystem functions; and (v) informative for management [14,68].

Table 2. Minimum data set (MDS) for soil health assessments.

Key Soil Health Parameters	Reason
BIOLOGICAL	
N mineralization	Capacity of the soil to supply N for crop growth
Microbial biomass	Source and/or drain of C and nutrients
Microbial activity	Related to the availability of nutrients and biogeochemical cycles
Soil respiration	Indicator for biological activity and organic matter
CHEMICAL	
Organic carbon	Important for soil structure and fertility, and water-holding capacity
Bio-available nutrient	Potential of nutrients to support plant development
pH	Availability of nutrients
CEC	Soil's availability to supply plant nutrients
EC	Related to soil structure, infiltration and crop development
Potential pollutants	Potentially harmful for plant growth and plant–soil system health
PHYSICAL	
Penetration resistance	Related to infiltration capacity and erosion and runoff processes
Aggregation	Indicator of soil structure and erosion protection
Infiltration	Indicator for erosion and runoff
Depth to hardpan	Roots growth potential
Texture	Important for soil water and nutrient transfer and retention
Water-holding capacity	Sufficient moisture to support plant growth

CEC, Cation exchange capacity; EC, Electrical conductivity. Compiled by authors from different sources [67,69,70].

Several methods can be used to define an appropriate MDS, including statistical tools (principal component analysis, multiple correlation, etc.), uncertain sets, expert opinion, and farmer/local knowledge [66]. Once the MDS has been established, linear and/or non-linear techniques can be applied to interpret the soil indicators. The non-linear scoring method is more representative of system function than the linear method but is more labor-intensive and requires more knowledge [71]. When individual indicators are scored, they can be integrated into a general index, which can be used to guide management decisions toward promoting the long-term sustainability of the soil resource [72]. These indices have an integrating character, combining multidimensional data on the physical, chemical, and biological properties of soil into a one-dimensional measure of soil health [59]. Many soil health indices can be found in the literature: additives, weighted, decision support system, integrated quality index, Nemoro quality index, etc. [71,73].

The benefits of using these indices are clear—they provide a unique value of soil health, which allows direct comparison between different soils [39]. They are also a decision tool that can help identify the most sustainable management practices [71]. However, they also have drawbacks. For example, the diversity of existing methodologies to build this one-dimensional index means that the resulting value for this index may vary between methods, making it difficult to interpret the results [39]. Furthermore, their use can sometimes give an overly simplified interpretation of the response of the complex agroecosystem to natural or anthropogenic disturbances [60].

4. Impact of Conservation Agriculture on Soil Health

CA measures have been put forward to restore or maintain major soil functions (C cycling and transformation, nutrient cycling, and soil structure maintenance), performing well in terms of crop yield, economic return, greenhouse gas emission mitigation, biodiversity conservation, and soil health improvement. Contrarily, there is an almost general consensus that certain practices of conventional agriculture to increase agricultural production have detrimental effects on the health of the soil. CA is proposed as an alternative to conventional management to ensure sustainability in the provision of ecosystem services through the soil [74], which can improve soil properties and associated processes [13,34].

The total impact of CA systems on soil health varies from location to location and is dependent on site-specific soil and climatic conditions, the amount of time operating under a CA system, features of CA practices (types of cover crops, intensity of the crop rotation, etc.), and the training and experience of farmers [34,70,75].

4.1. Influence on Soil Physical Properties

Traditional agriculture through CT provokes a significant alteration of physical soil properties, such as degradation of the structure, compaction problems, soil bulk density, soil penetration resistance, etc. CA is able to reduce these negative effects of CT. Some of the most important parameters of soil physical health are described in the following sections.

4.1.1. Soil Structure

Soil structure is an important parameter in the sustainability of agroecosystems, due to its role in physical, chemical, and biological dynamics of soil, and determines its resistance to degradation by water erosion. Aggregate stability against different stresses (rainfall, tillage, etc.) is a useful measure to determine soil structural stability.

According to Bronick and Lal [76], soil structure can be significantly modified through management practices. Soil structural development can be enhanced by management systems that reduce soil disturbances, increase organic matter inputs, increase plant cover, and improve soil fertility. In this sense, one of the major negative impacts of conventional long-term tillage is the deterioration of the soil structure due to the reduction in soil organic matter [34].

There is a positive correlation between the mean weight diameter of soil aggregates and total organic carbon content [77,78]. The soil organic matter (SOM) promotes macroaggregate formation; meanwhile, soil aggregates improve the physical protection of organic matter [79]. Higher aggregate stability under CA is the result of the interaction of various factors: (i) the retention of organic residue on the soil surface protects soil aggregates from raindrop impact and avoids soil compaction [80]; (ii) decomposing organic matter increases the aggregation process [81]; (iii) no soil disturbance increases fungal populations and the persistence of root networks that encourage the stability of the aggregates [82]; and (iv) reducing soil disturbance in CA systems allows the development of a more stable soil structure than in CT systems [83]. Numerous studies have reported an improvement in the stability of soil aggregates due to the application of CA practices [84–86]. In a study in Zambia, CA practices with residue retention and crop rotation showed higher aggregate stability (41–45%) compared with conventional ploughing practices (24%) [87]. This improvement in the stability of the aggregates is a function of the type of soil. Thus, Nyamangara et al. [88] reported a greater increase in the stability of the aggregates due to CA practices in soils high in clay (18.1%) than in soils low in clay (9%), compared to CT. The increase in aggregate stability due to CA practices is greater in the topsoil layer, decreasing with depth. Zhang et al. [89] reported a greater increase in the stability of soil aggregates in the surface layer (0–20 cm) than in the subsurface layer (20–40 cm) in treatments with straw return compared to treatments without straw. A study by Eze et al. [90] with a long-term experiment found that maize-based CA systems result in significant changes to soil hydraulic properties that correlate with improved soil structure. The findings showed increases of 5–15% in total porosity, 0.06–0.22 cm/min in Ksat (saturated hydraulic conductivity), 3–7% in fine pores for water storage, and 3–6% in plant-available water capacity. Furthermore, according to these authors, the maize monocrop under CA practices had an impact on soil hydraulic properties comparable to that of the maize–legume associations.

These improvements in the soil structure, due to CA practices, promote other beneficial effects on the soil, such as higher infiltration rates, greater protection against erosion, increased water-holding capacity, improved habitats to support microbial activity, etc.

4.1.2. Bulk Density

The bulk density is one of the most common physical parameters to assess the impact of tillage and crop residue on agricultural soils, as it is an indicator of the soil's compaction and reflects the soil's ability to function in terms of structural support, water and solute movement, and soil aeration. High bulk densities cause root impedance and lead to poor crop emergence. There is no consensus regarding the effect of CA on soil bulk density, as some studies reported a higher soil bulk density with CA compared to CT [91,92], while others have not found significant differences [86,93] or reported lower soil bulk density in CA in comparison to CT [88,94]. These differences in bulk density in the different trials may be due in part to the typology of the farm. Greater topsoil bulk density recorded in studies on large farms in the USA or Australia can be the result of compaction due to heavy no-till machinery used, but this does not occur in smallholder farms in developing countries, where cultivation is performed manually or with animal draft power [95].

In a global meta-analysis, Li et al. [96] claimed an average increased bulk density of 1.4% in a no-tillage (NT) system with residue retention compared with CT. However, they also concluded that the greatest soil compaction value in conservation tillage practices was below the threshold value that limits plant growth.

According to Mondal et al. [97], no significant differences in bulk density were found in soil depth up to 15 cm after the implementation of CA. However, a greater bulk density was determined in a traditional rice–wheat cropping system than in treatments with CA at soil depth of 15–30 cm. Generally, bulk density was greater for CA than CT for soil depths within the plow layer [13,98]. However, in the top few centimeters in NT, the accumulation of crop residues and soil organic carbon (SOC) on the soil surface led to a lower bulk density [99]. Sometimes, the amount of residue is not enough to limit the increase in bulk density under no-tillage systems. In these cases, the residues can be shredded, thus increasing the covered area and mitigating the hardening of the soil [98].

The effect of conservation tillage systems (minimum/reduced tillage and no tillage) on the apparent density of the soil is not immediate; it is necessary that a few years elapse from the conversion from CT to reduce it [100]. The crop residue incorporation into the soil in conservation tillage plays a pivotal role in decreasing bulk density. In this sense, Nyamadzawo et al. [101] attributed lower bulk density in CA systems to the presence of higher levels of organic matter, which tends to improve soil structure and increase porosity. In contrast, Mondal et al. [102] reported a similar bulk density under CT and NT systems.

According to Islam and Reeder [103], soil bulk density at 0 to 15 and 15 to 30 cm depths under long-term NT decreased significantly compared to CT. At 0 to 15 cm depth, the greatest difference compared to CT occurs with 35 years of continuous zero tillage. The bulk density at depths of 15–30 cm decreased linearly over the years of NT. This decrease in bulk density is associated with an increase in total soil porosity. In a long-term study of maize (*Zea mays* L.) based crop rotations, the bulk density under CA practices (zero tillage and permanent raised beds) was reduced by 4.3–6.9% in soil depths of 0–30 cm compared with CT. In deeper soil layers (30–60 cm), differences between management systems were non-significant [104].

4.1.3. Surface Seal and Soil Crust

Bare soil in conventional systems leads to increased surface seal and crust formation due to the lack of protection against the impact of raindrops. The impact of rainfall causes the breakdown of soil aggregates and the release of finer particles, which are redistributed by the near-surface and fill the most superficial pores. This process causes sealing and surface waterproofing, decreasing water infiltration and, consequently, enhancing the runoff and soil loss [105]. Surface sealing has a negative impact on the physical characteristics of soil, which ultimately affects crop yield [106].

The presence of crop residues in CA practices can help protect the surface of the soil from raindrop impact and prevent surface sealing. In structurally unstable soils or regions where crusting is a serious problem, the maintenance of adequate surface cover is paramount to avoid surface sealing and crust formation [107]. When CA is practiced in the absence of effective soil mulch cover, surface sealing may occur. Usón and Poch [108] showed that reduced tillage did not reduce crust formation in Mediterranean conditions, due to the difficulty of establishing an effective ground cover. In certain circumstances, the quantities of biomass produced and retained in CA systems can be insufficient to avoid soil crusting and compaction [109], but increasing residue above a threshold can have no effect because of sufficient raindrop impact interception [110]. According to Page et al. [111], the surface sealing, due to the inadequate residue cover and the lack of tillage, particularly in drier regions, can be one cause of yield loss in CA systems. In situations where little surface cover from crop residue is available, the creation of surface roughness using strategic tillage is a viable option to break soil crusts, improve water infiltration, and reduce runoff [112].

Thus, a permanent soil surface cover by crop residues significantly reduces surface sealing [113]. Various studies report on the preventive effect against surface sealing in CA exerted by crop residues on the soil surface, protecting the soil from the direct impact of raindrops [114,115]. In this sense, Castellanos-Navarrete et al. [84] reported that in CA systems, soil crusts were not present on the soil surface; however, soil under CT with poor aggregate stability showed soil crust formation.

4.1.4. Soil Compaction

Soil compaction is a form of physical degradation that consists of the densification of the soil, which often results in the destruction of the soil structure; a reduction in biological activity, porosity, and permeability; an increased risk of erosion; a restriction on root development; and, consequently, decreased crop performance. On farmland, the traffic of heavy agricultural machinery is the main cause of soil compaction, and its magnitude increases with the number and intensity of tillage operations and when these are carried out in inappropriate soil moisture conditions. The influence of the machinery is so important that "controlling in-field traffic" is considered a component of CA. Recommended practices include bed planting that reduces compaction by confining traffic to the furrow bottoms [116], or the application of fertilizers at the time of seedbed preparation or seeding to reduce machinery transit [117].

In the long term, tillage promotes soil compaction and the formation of a plough pan in the sub soil. Crop rotation, cover crops, and the addition of crop residues in CA systems can reduce soil compaction. Mondal et al. [118] reported a reduction in the subsurface compaction by CA systems, with a soil penetration resistance significantly less in the 15–30 cm layer under CA. This can have a positive impact on root morphology, which can contribute to increased crop yield. According to Hamza and Anderson [119], increasing the SOM through the retention of crop residues and crop rotations that include plants with deep, strong taproots can delay or prevent soil compaction. The use of root crops in cover crops can significantly reduce soil compaction. In this sense, Islam and Reeder [103] showed that oilseed radish significantly decreased compaction to about 75 cm, with an average improvement effect of about 40% compared with soil between the rows. Chen and Weil [120] reported that the use of cover crops improved maize root penetration in compacted soils and increased the availability of surface soil water. In a study in India, Parihar et al. [104] reported that the CA practices of NT and permanent raised beds reduced the penetration resistance by 15.9 and 30.7%, respectively, compared to CT in maize rotations.

According to Holland [17], there is evidence that the long-term use of conservation tillage can, in certain situations, lead to soil compaction. Similarly, Munkholm et al. [121] concluded that direct drilling provoked the compaction of the arable layer below seeding depth on sandy loam. Thus, the long-term viability of conservation tillage techniques depends on a proper crop rotation [122] and/or the use of strategic or occasional tillage in soils under NT [123,124].

4.1.5. Soil Moisture Content

Water scarcity is one of the greatest challenges facing humanity in the coming decades [125]. CA practices improve soil moisture availability, especially under low-rainfall conditions and could contribute to maintaining crop yield in a changing climate scenario [126]. In this sense, several studies have reported a greater availability of water in CA systems with respect to CT [85,127–129]. Residue retention and cover crops in CA systems improve infiltration [96] and reduce runoff rates [127] and evaporation losses [130,131], as they protect soil from direct contact with solar radiation and act as a barrier to air flow, contributing to higher soil moisture.

No-till practices and residue cover improved soil–water relations in a study in Malawi, with an average increase in soil water content of 22 and 18 mm in NT and CA, respectively, compared to CT [132]. A meta-analysis carried out by Zhao et al. [133] concluded that crop residue retention led to an increase in soil water content by 5.9% compared with crop residue removal. In a rice system study, NT with surface residue and minimum tillage with residue incorporation had higher soil moisture than CT with residue removed [134]. Similarly, Ghosh et al. [127] reported that soil moisture conservation was 108% higher under CA than conventional agriculture plots. Mondal et al. [135] showed that the soil water content was 14% higher in CA relative to CT in the sub-surface layer (15–30 cm), while in other layers, there were no significant differences. A study by Chalise et al. [136] with a corn–soybean (*Glicine max* L.) system highlighted that the use of cover crops with residue returned improved the soil's hydrological properties and increased soil volumetric water content and soil water storage. In maize crops in the sub-humid and semi-arid regions of Kenya, NT with residue retention significantly increased soil water content compared to CT [137]. According to Sindelar et al. [138], residue removal decreased plant-available water by 32% in soil depth of 0 to 5 cm and by 21% in soil depth of 5 to 10 cm. In this context, Li et al. [96] reported that NT with residue retention increased soil-available water capacity by 10.2% compared with NT without residue retention. Similarly, Choudhary et al. [139], in a pearl millet (*Cenchrus americanus* L.)–mustard (*Brassica juncea* L.) rotation system in rainfed semi-arid regions, reported higher soil water content throughout the season in plots with residue retention than in the no-residue plots.

In irrigated plantations, crop residues conserve soil moisture and delay irrigation timing, allowing farmers to save irrigation water. In this sense, Balwinder-Singh et al. [140] found that the use of residue mulch of 8 t ha^{-1} in irrigated wheat led to saving 75 mm of irrigation water. Comparably, Gupta and Sayre [141] reported that NT practices allowed saving between 13 and 21% of irrigation water compared to CT systems. Assefa et al. [142] highlighted that CA practices with a drip irrigation system lessened water needs by about 14–35% for various crops. In irrigated onion and garlic plantations in Ethiopia, CA plots received 49 mm less water than CT treatment [143]. In addition, Jat et al. [144] showed that a CA-based maize–wheat system decreased irrigation water use by 64% compared to conventional management.

Based on field observations, many meta-analysis studies have contrasted the effects of different tillage practices on determining crop production, evapotranspiration, and water-use efficiency (WUE) [122,145–147]. Evidently, CA practices enhance WUE, as the findings by Lu [148] suggested that crop residue return can increase crop yields and WUE. In a study in a semi-arid region of China, Sun et al. [149] stated that conservation tillage significantly enhanced WUE and crop yield with respect to CT. According to Das et al. [150], experimental plots under CA practices had significantly higher WUE and significantly lower water use than CT. That is, the zero tillage with planting on permanent broad beds and residues treatment had higher WUE than the CT. Moreover, zero tillage with planting on permanent broad beds and residues treatment had higher WUE than zero tillage with planting on permanent narrow beds and residues. Thus, CA practices improve water productivity due to their water harvesting and water conservation effects [151].

Although most studies have found positive effects of residue retention on soil water, some negative consequences can also occur in certain environments, such as in rainfed areas. Cover crops in sloping lands with rainfed fruit crops do not result in economic return; however, the environmental return is highly important [152,153]. Cover crops, however, compete for resources (plant nutrients and water) with the trees, which can lead to a decline in productivity [154,155]. In other words, the cover crop benefits are more weather-specific than site-specific because when precipitation is low or not properly distributed, the water reduction after cover crops could have a negative effect on the cash crop growth and yield. In sloping olive orchards, a greater available soil water content was found under a non-tillage system with plant strips (barley and native vegetation) of 4 m width than for a non-tillage system without plant strips, particularly beneath the tree canopies [156]. In addition, Castellini et al. [157] reported the positive influence on soil hydraulic function of minimum tillage compared to non-tilled soil on olive plantations. In this context, Abazi et al. [158], examining rainfed olive orchards, determined that the use of cover crops in a Mediterranean environment has a negative impact on olive transpiration (25% average reduction), although this impact can be attenuated by early-date killing of the cover crop in the middle of March.

Contrarily, in high-rainfall areas, the greater retention of soil moisture under CA can also lead to waterlogging, with associated negative effects on crop growth and yield [91,159,160].

4.1.6. Water Runoff and Soil Loss

Conventional agriculture promotes runoff and soil loss by causing soil compaction, crusting, and surface sealing, and by decreasing porosity. In contrast, CA is associated with a reduction in soil erosion [161] (Figure 4), among other benefits. In particular, in rainfed sloping lands in Mediterranean environments, the crop residue retention and cover crops in CA systems protect the soil surface from raindrop impact and reduce the detachment, displacement, movement, and deposition of soil particles, which causes soil sealing and crust formation [162]. Furthermore, cover crops and their residues slow the velocity of agricultural runoff along the slope, improving infiltration and preventing soil erosion [163].

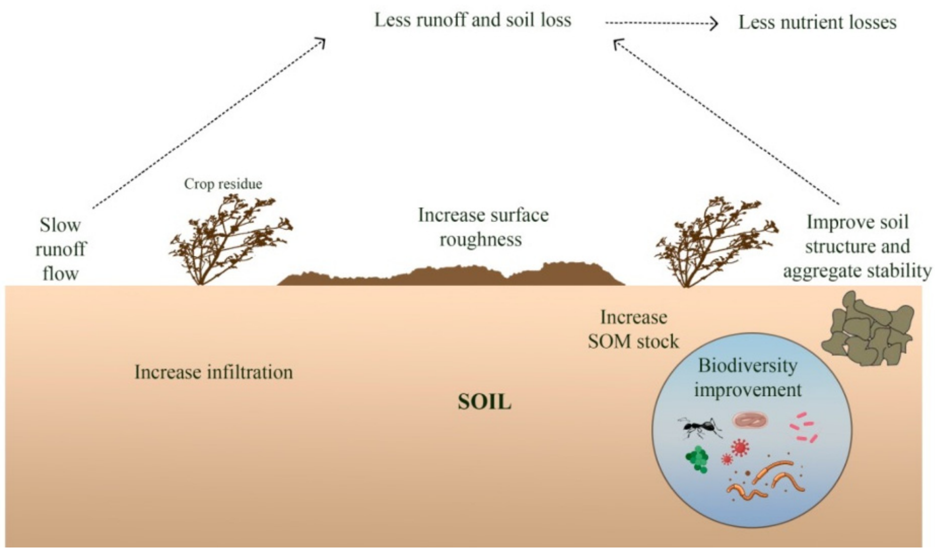

Figure 4. Effect of conservation agriculture on water erosion.

According to Thierfelder and Wall [164], plots with reduced tillage and surface residue retention had less runoff and soil erosion than conventionally tilled plots. Under semiarid rainfed conditions in western India, Kurothe et al. [165] reported that NT reduced runoff by 16.2% and soil loss by 37.2% compared to CT. Panachuki et al. [166] reported a significant reduction in runoff and soil loss in an NT system with soybean residues, compared to an NT system without residues. The retention of residues on the soil surface exerted a greater protective effect than their incorporation into the soil. In an experiment in northern Ethiopia with a wheat (*Triticum* sp.)–teff (*Eragrostis tef*) rotation, after 3 years, soil loss and runoff were significantly lower (5.2 t ha^{-1} and 46.3 mm) in permanent raised beds with 30% standing stubble compared to CT without surface residue (24.2 t ha^{-1} and 98.1 mm) [167]. Ghosh et al. [127] reported that mean runoff coefficients and soil loss with CA plots were ~45% less and ~54% less than conventional agriculture plots, respectively. The efficiency by which surface residues control runoff and soil losses increased with the amount of residue. In this context, Ranaivoson et al. [168] reported that residue levels of 1.5 to 4.5 t dry matter ha^{-1} decreased water runoff by about 50%, and residue amounts of 2 to 4 t dry matter ha^{-1} reduced soil erosion by about 80% compared to bare soil. The amount of residue necessary to reduce runoff and soil loss varies depending on the slope of the field and the intensity or amount of rainfall [169].

According to Du et al. [170], conservation practices decrease surface runoff and erosion, on average, by 67 and 80%, respectively, compared with conventional practices; the use of cover crops is what most reduces erosion and runoff. In northern Ethiopia, permanent raised beds with contour furrows at 60–70 cm intervals significantly reduced runoff and soil loss compared to traditional ploughing, with 255 and 653 m^3 ha^{-1} runoff and 4.7 t ha^{-1} and 19.5 t ha^{-1} soil loss, respectively [171]. In another study in Ethiopia, CA practices also reduced erosion and runoff. CA registered a runoff coefficient of 18.8% and a soil loss of 14.4 t ha^{-1} yr^{-1}, while for plain tillage, these parameters were 30.4% and 35.4 t ha^{-1} yr^{-1}, respectively [172].

Terracing is one of the oldest techniques for the conservation of water and soil in mountainous regions; terraces are built along contour lines to increase the arable surface area. Deng et al. [173] pointed out that these structures provide many ecosystem services, including the control of runoff and sediment by over 41.9 and 52%, respectively, and the improvement of crop yield and soil water content by 44.8 and 12.9%, respectively. In this context, the implementation of cover crops in the taluses of orchard terraces is a key factor for preventing their collapse by water erosion, lessening the runoff, soil loss, and pollution risk in low lands [174,175].

The rainfed plantations in the Mediterranean mountains with traditional practices provoke high soil erosion rates, compromising their long-term sustainability. Francia et al. [176] evaluated erosion rates by the effect of NT, CT, and cover crops in olive (*Olea europea* L.) orchards of 25.6, 5.7, and 2.1 t ha^{-1} yr^{-1}, respectively. Similarly, Gómez et al. [177] determined the soil erosion values for NT, CT, and cover crops as 6.9, 2.9, and 0.8 t ha^{-1} yr^{-1}, respectively. Recently, Cárceles et al. [178] reported that the strategies based on CA proved to be effective. The combination of minimum tillage with plant strips in almond (*Prunus dulcis* L.) and vineyard (*Vitis vinifera* L.) orchards was a more efficient practice in terms of water erosion control than only minimum tillage, averaging declines in soil erosion and runoff rates of 36 and 39%, respectively. Similarly, for olive crops, the association of minimum tillage and plant strips compared to a no-tillage system was able to reduce both soil erosion and runoff rates by 36%. Thus, the implementation of soil management measures based on cover crops is essential for hillslopes and low-fertility soils, encouraging their sustainability.

4.1.7. Soil Temperature

Soil temperature is an important property that affects crop growth and development and impacts numerous soil physical, chemical, and biological processes. Cover crops and retention of residues in CA systems can help moderate and stabilize the fluctuations in soil temperature during the crop growth period as compared to systems with bare soil [34], which can be especially important in regions with large fluctuations in temperatures [179]. The magnitude of variation in soil temperature due to management is higher in the soil top layer, decreasing in the lower layers [180]. Rai et al. [181] reported that the CA practices with mulching were effective for the reduction in soil temperature fluctuations with depth.

Moreover, crop residue retention on the soil surface reflects sunlight and isolates soil from high temperatures and thus reduces evaporative losses of water. The effect of residues on the soil temperature changes depending on the color of the residues. According to Sharratt and Campbell [182], dark residues resulted in higher mid-day temperatures compared to lighter-colored residues. Retention of residues on the soil surface in CA systems decreases daytime soil temperature [183]. Li et al. [184] reported that the crop residue remaining on the soil surface in conservation tillage systems can lessen the soil temperature change because surface residue both increases the reflection of incident solar radiation and acts as an insulating barrier between the soil surface and the warmer or colder atmospheric air above [185]. In this context, lower maximum soil temperature and higher minimum soil temperature in the 0–5 cm surface soil layer were recorded under minimum tillage with mulch treatments, compared to the CT with no-mulch treatment [186]. According to Gupta et al. [187], a zero-tillage system with residue cover had a lower soil temperature than a zero-tillage system without residue and moldboard ploughing. Guzman and Al-Kaisi [188] also reported warmer soil temperatures when crop residues were removed. In the summer season, Oliveira et al. [189] reported that daytime soil temperature in a zero-tillage system with residue retention was 2–8 °C lower than that in the conventional tillage system.

In addition, this lower soil temperature under CA systems in hot regions can help improve plant growth and crop yield [190]. In cooler climates, however, reduced soil temperature from residue cover may be a disadvantage because it can delay seed germination and plant maturity and negatively affect yield [91,191]. In this sense, Chen et al. [192] reported that straw retention decreased soil temperature in spring and delayed the development of winter wheat up to 7 days, on average reducing the final grain yield by 7% compared to systems without straw retention. To address this issue and attempt to adapt this soil management system to temperate zones, the withdrawal of residues from the seed strip has been suggested [191,193].

Tillage operations can also affect soil temperature by changing soil surface microtopography, as inclined ridge surfaces absorbed about 10% more solar radiation than flat surfaces, according to Radke [194]. Additionally, Shen et al. [195] claimed that tillage had significant effects on soil temperature in 10 of 15 weekly periods, with the temperatures of non-tilled soils being 0–1.5 °C lower than those of moldboard plough soils when residue was not returned in the previous autumn. Moreover, the ridge tillage showed no clear advantage over non-tilled soils in increasing soil temperature.

Finally, other studies reported an increase in soil temperature due to stubble retention [196], which helps crops survive during the cold winter and reduces emergence time, improving crop productivity. Kahimba et al. [197] showed that in the Canadian prairies, the presence of a crop cover or perennial vegetation resulted in relatively warmer soil profile temperatures and shallower depth of frozen soil layers. Moreover, according to Al-Darby et al. [198], despite the delay in the growing season due to the lower soil temperature in the CA systems, there was no reduction in dry matter and corn grain yield due to the greater amount of accumulated water.

4.2. Influence on Soil Chemical Properties

Agronomical practices may change soil chemical properties and thus fertility. The responses of soil chemical fertility to tillage practices and the magnitude of these changes depend on several factors: soil type, cropping system, climate, fertilizer application, and management practices. Long-term tillage causes severe SOM depletion in agroecosystems and can lead to soil degradation. In contrast, CA practices increase chemical quality by improving the SOC storage and nutrient dynamics. The impacts of CA techniques on some of the most relevant soil chemical properties are presented in the following sections.

4.2.1. Soil Organic Carbon

SOM is a keystone indicator of soil quality because it is linked to other physical, chemical, and biological soil quality indicators [199], playing a crucial role in soil fertility and sustainability, as it increases soil aggregate stability and water retention and provides a reservoir of essential nutrients for crops [200].

In addition, there is currently a growing interest in increasing the stock of SOC in agroecosystems because this can help mitigate climate change. In agricultural practices with high organic inputs, reduced or no tillage and permanent soil cover are capable of increasing SOC stock, acting as a carbon sink and thus mitigating the agricultural impacts on climate change [201,202]. On the other hand, the increase in SOC has positive effects on the quality of the soil, and this can improve the soil resilience, contributing to adaptation to climate change [203].

Soil tillage increases the decomposition rates of SOM, as it implies an alteration of the soil structure and the exposure of the organic matter retained in the micro-aggregates [204]. In a study by Repullo-Ruibérriz de Torres et al. [205], over a 4 year monitoring period on an olive plantation, SOM increased by the effect of different cover crops (*Brachypodium distachyon*, *Eruca vesicaria*, *Sinapis alba*, and native vegetation) between 10.9 and 14.3 Mg ha^{-1} at 0–40 cm soil depth.

The conversion of CT to conservation tillage increases the accumulation of SOC in the soil surface layer. CA increases SOC stock through the reduction in SOC losses by oxidation and erosion, the increase in organic carbon inputs to the soil (plant residues), or a combination of both factors [206,207]. Figure 5 summarizes conservation agriculture practices that may influence SOC stock increases.

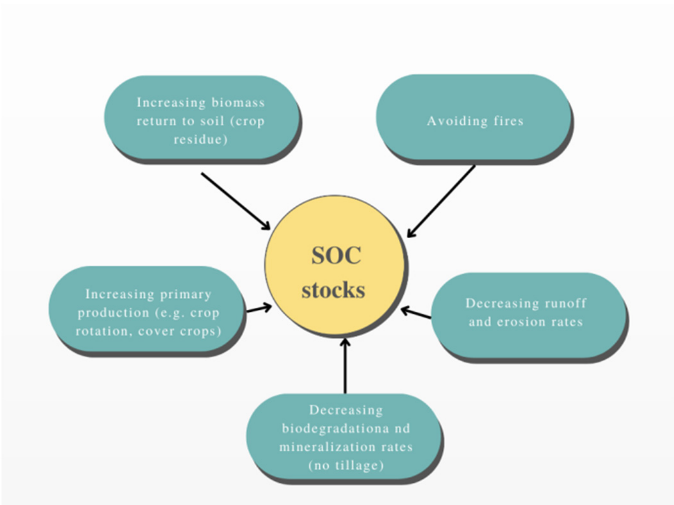

Figure 5. CA practices that increase SOC stock.

Changes in SOC storage with CA practices depend on various factors such as the quantity and quality of plant residues, time period, or edaphoclimatic characteristics [208]. These effects are most evident in the topsoil. In this context, the global analyses by Luo et al. [209] and Mondal et al. [210] indicated that a no-tillage system benefited the storage of SOC only in the upper 10 cm of the soil. Camarotto et al. [211] reported that CA increased the SOC stock in the 0–30 cm layer (0.25 Mg C ha^{-1} yr^{-1}) compared to conventional agriculture. In a maize–mustard rotation, Pooniya et al. [212] reported that CA systems had greater values for SOC than CT at soil depths of 0–0.15 m and 0.15–0.30 m, while at 0.30–0.45 m, there was no difference. Therefore, to obtain a more accurate assessment of CA practices' impact on SOC, the entire plow depth should be sampled [213]. In addition, comparing the results of experiments that compare CA with conventional systems is complicated, since they depend on several factors: depth of the investigated soil, sampling methodologies, duration of the study, edaphoclimatic variability, and crop type [211]. In irrigated almond orchards in Mediterranean semi-arid regions, according to Repullo-Ruibérriz de Torres [214], a crop mixture (65% barley and 35% vetch) and barley cover crops showed higher potential for C sequestration than spontaneous vegetation, augmenting the SOC by more than 1.0 Mg ha^{-1} after two monitoring seasons.

Long-term CA increased SOC content in the 0–5 cm soil layer in an intensive cereal-based cropping system in India [215]. In a study in northern Italy, Perego et al. [216] showed that CA systems in the medium term resulted in significantly higher SOC content and SOC stock than conventional systems. A study in rice (*Oryza sativa*)–wheat cropping systems in a South Asian region showed that the stratification and storage of SOC were higher under CA practices compared to intensive tillage-based conventional agricultural practices [217]. In a meta-analysis to evaluate the effects of minimum tillage and crop residue retention on SOC stock in 0–30 cm soil depths, Li et al. [218] reported that a no-tillage system with residue retention and a reduced tillage system with residue retention increased SOC stock by 13 and 12%, respectively, in comparison to CT. In a rice–wheat system, after 7 years, NT combined with partial residue retention increased SOC stock at 0.6 m depth [219].

4.2.2. Soil pH

The effect of conservation practices on soil pH is generally restricted to the topsoil layers. The effect of crop residues on soil pH depends on the chemical composition of the residues and the properties of the soil [220]. Residues high in ash alkalinity and N, such as some legume residues, will have a greater effect on pH compared to residues with lower content, such as wheat [221]. The initial pH of the soil has a substantial impact on the change in soil pH through the incorporation of crop residues, as it affects the mineralization of N in the residue and the rate of decomposition of organic compounds [222]. Similarly, a long-term study by Muchabi et al. [223] of fields under CA and CT highlighted a significantly higher soil pH (6.18 vs. 5.62), SOC, nodulation, and biological N fixation as a result of CA implementation after 7 years of practice. These findings are comparable with those reported earlier by Duiker and Beagle [224] and Umar et al. [225], who ascribed the upward changes in soil pH to the buffering effect of accumulated organic matter under CA. Recently, Sinha et al. [226] reported that the soil pH generally lowered under zero tillage compared to CT, being the most notable in acidic soil sites, where pH decreased by up to 0.4 units; the lower the initial soil pH, the higher was the decrease in pH under zero tillage.

Several studies have reported an increase in acidity in topsoil layers under reduced tillage treatments in comparison with CT [227,228]. This increase in acidity is attributed to a greater accumulation of soil organic matter on the soil surface in NT, which decomposes and produces acidity. In the deeper layers, there is an increase in pH because the soluble component of the residues moves through the soil profile and contributes to the alkalization of the subsoil layers [228,229]. In acid soils, various authors have reported that CA systems increased soil pH [229,230]. The organic matter that increases with CA practices tends to bring the pH to neutral or slightly acidic by buffering the pH of the soil. A long-term CA experiment carried out by Ligowe et al. [231] registered, on average, 14 and 21% higher pH and SOM, respectively, than the conventional practice, with a positive correlation (74%) between SOM and pH found during the fifth monitoring season.

4.2.3. Cation Exchange Capacity

The cation exchange capacity (CEC) is the ability of a soil to retain and release positive ions due to its content of clays and organic matter, and is considered an indicator of soil fertility. CA practices increase SOM content, and this provokes an increase in CEC [232], as it increases the amount of negative charges [233]. In this context, Ben Moussa-Machraoui et al. [234] reported a positive correlation between SOM and CEC. This increase in CEC driven by improvements in SOM via cover cropping can also lead to an increase in yield stability [235].

According to Sá et al. [233], CEC increased by 0.37 cmolc kg^{-1} for every gram of C per kg of soil. The effects on CEC are generally limited to the topsoil, which is where the SOM content is increased [224]. In this context, Williams et al. [235], in a study in the USA, showed that cover cropping increased SOM compared with no cover crop, implying a rise in CEC. In a tropical soil under no-till farming, CEC increased by 25% in the top soil layer (0–20 cm) with every 1.8 kg m^{-2} of stored organic carbon [236]. After 5 years, CEC increased in the topsoil when residues were retained compared to soils without residue [237]. Sithole and Magwaza [228], in a long-term study in South Africa, showed that CEC was affected by tillage practices. On average, CT resulted in a significantly lower (71.9 mmolc.kg^{-1}) CEC than rotational tillage (109 mmolc kg^{-1}) and NT (114 mmolc kg^{-1}). A long-term field experiment under rice-based cropping systems showed that the CEC was higher in NT than in CT, amounting to 13.04 and 9.76 cmol (p+) kg^{-1}, respectively [238]. In a tropical rainfed agroecosystem, the adoption of minimum tillage provoked an 11.2% increase in CEC compared with the CT system [239]. Moreover, Mloza-Banda et al. [93] reported a significant increase in CEC after 2 years of conversion to CA (15.24 cmol (+) kg^{-1}) compared to annual ridge tillage (13.38 cmol (+) kg^{-1}). Similarly, Zerihun et al. [240] reported an improvement in CEC with crop rotation and intercropping in CA systems.

Conversely, Fonteyne et al. [241], in a study in Mexico of 20 maize-based trials, did not register differences in CEC between CA and local conventional practices. Comparably, Mrabet et al. [242] did not find significant differences in CEC between CA and CT in a study in Morocco. The lack of difference between the different management systems may be due to the short duration of the studies or due to the influence of local soil conditions.

In other studies, a lower CEC was observed in soils under CA due to a decrease in pH, which resulted in a decrease in pH-dependent cation exchange sites [227,243].

4.2.4. Nutrient Availability

CA practices have a significant impact on nutrient distribution and transformation in soil; thus, they can strongly influence the soil nutrient dynamics [178]. That is, CA systems that cause an increase in organic matter due to the addition of residues can produce a rise in nutrient reserves for plants, registering higher concentrations of nitrogen (N) [244,245], phosphorus (P) [246,247], potassium (K) [228,247], calcium [248], magnesium [249], zinc [250], and manganese [249] in the soil. The nature of crop residues and their management has a significant influence on the plant nutrient availability of soils. For example, in the case of N, the addition of legume residues with a low C/N composition can result in N mineralization, whereas cereal residues with a high C/N composition can temporarily immobilize N during the decomposition process [251,252]. In a review study on the effects of crop residues under CA, Ranaivoson et al. [168] reported, in general, a higher increase in soil mineral N in the case of legume residues than in the case of cereal residues. The availability of nutrients with the retention of residues is also a function of other factors, such as the amount of surface residues or the proportion of soil covered by them [168]. The availability of nutrients in the soil can also be affected by the change in topsoil pH due to CA practices [253].

A greater amount of residues stored in the soil with CA systems does not always lead to a greater availability of nutrients for plants. Soon after CA is implemented, while total stores of N may be higher, the amount of plant-available N may decrease due to lower mineralization rates and higher N immobilization rates [111]; in this case, it is necessary to apply N fertilization to maintain the yield [228].

An NT system with a total absence of soil mixing can lead to the stratification of immobile nutrients such as P and K in the surface layers of soils [254]. In dry areas of Morocco, Mrabet et al. [242] showed that NT caused surface enrichment of P and K compared with CT. This can be a problem, especially in arid regions, as drought conditions can reduce nutrient uptake from the dry soil surface, inaccessible to plant roots [255]. Furthermore, these conditions can increase the risk of N and P losses by surface runoff [256]. Higher moisture content due to CA practices can lead to N losses due to denitrification [257]. Finally, according to Morugán et al. [258], the permanent cover crops in the alleys led to higher increases in SOC and soil N; however, this practice was related to negative effects on available P in the soil. Similarly, Sujatha et al. [259] claimed that the extensive root system of legumes was beneficial for improving their ability to release organic acids from their roots that enhanced K availability in soil. Table 3 shows the implantation effect of

CA practices compared to CT in hillslope farming with rainfed olive orchards in southeast Spain [260].

Table 3. Effect of CA practices on soil physico-chemical parameters in olive orchards throughout 3 year monitoring period (SE Spain).

Soil Management	Year	pH (H_2O)	MCP (%)	BD (g cm^{-3})	SOC (g kg^{-1})	N_T (g kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	CEC (cmol (+) kg^{-1})
Minimum tillage and spontaneous vegetation strips	1st	7.5 (±0.1)	11.4 (±4.3)	1.17 (±0.04)	8.4 (±4.8)	0.45 (±0.03)	6.4 (±2.6)	68.7 (±18)	15.8 (±3.0)
	3rd	7.6 (±0.2)	12.6 (±3.6)	1.24 (±0.08)	10.2 (±7.5)	0.68 (0.05)	7.0 (±3.5)	77.7 (±26)	16.7 (±7.8)
Minimum tillage and legume strips	1st	7.5 (±0.2)	10.0 (±3.4)	1.18 (±0.14)	8.0 (±5.7)	0.58 (0.01)	4.6 (±1.7)	84.4 (±14)	10.2 (±4.4)
	3rd	7.7 (±0.5)	11.3 (±3.2)	1.26 (±0.07)	8.9 (±3.4)	0.67 (0.08)	5.2 (±4.2)	94.7 (±22)	14.7 (±7.1)
Conventional tillage	1st	7.5 (±0.1)	11.7 (±2.8)	1.20 (±0.09)	8.3 (±3.4)	0.55 (±0.03)	6.9 (±3.9)	67.5 (±18)	11.8 (±3.5)
	3rd	7.6 (±0.2)	10.1 (±3.1)	1.10 (±0.15)	7.2 (±2.7)	0.48 (±0.05)	7.2 (±2.7)	63.7 (±26)	12.7 (±7.4)

BD, bulk density; MCP, macroporosity; SOC, soil organic carbon; NT, total nitrogen; P, Olsen's extractable phosphorus; K, available potassium; CEC, cation exchange capacity. Values in parentheses are standard deviation.

According to Belay et al. [261], in supplementary irrigation vegetable production systems, CA practices can optimize nutrient use by decreasing nutrient losses through runoff and leaching. In this respect, several studies show that CA practices reduce the loss of nutrients via runoff or nutrients adsorbed in sediments lost by water erosion [176,262–265]. In this context, Jordan et al. [266] registered an 81% decrease in total P loss and a 94% decrease in organic nitrogen with non-inversion tillage compared with plow. In citrus orchards, the straw mulching covering the soil surface reduced runoff and sediment losses and subsequently decreased nutrient losses; the total nitrogen and phosphorus losses were significantly decreased by the straw mulching treatment compared with conventional treatments without mulching [267]. Liu et al. [268], using the Soil and Water Assessment Tool (SWAT), concluded that conservation tillage and contour farming can help reduce runoff by 15.99% and 9.16%, total nitrogen losses by 8.99% and 8%, and total phosphorus losses by 7% and 5%, respectively. In a study by García-Díaz et al. [269], the efficiency of using groundcover in vineyards to reduce mineral N losses via runoff was demonstrated.

As stated by Dinnes et al. [270], the strategies for reducing NO_3 loss through leaching can include CA practices by using cover crops, diversifying crop rotations, and reducing tillage. Cover crops or intercrops with deep-rooted plants reduce nutrient loss, intercepting leached nutrients from the root zone and returning them to the soil surface via mulch or as green manure. Wyland et al. [271] reported a 65–70% reduction in nitrate leaching from cover-cropped plots compared with the fallow control. In a study in Italy, CA practices had lower NO3 concentrations below the maximum rooting zone compared to conventional agricultural practices, thus reducing NO_3 leachate to groundwater [272]. According to Camarotto et al. [245], continuous soil cover and cover crops in CA systems reduced N leaching compared to conventional agriculture.

4.3. Influence on Soil Biological Properties

Soil biota plays a relevant role in soil health and sustainable crop production by supporting important functions such as soil aggregation, soil aeration, nutrient cycling, and bio-control, or the suppression of plant pathogens. Anthropogenic activities and especially intensive agriculture cause a considerable loss of soil biodiversity. Sustainable land uses are linked to the conservation of soil biological diversity [273]. Higher biodiversity means greater resilience to disturbances in the soil system [60]. The response of soil microorganisms and biochemical properties to soil management practices is measured by parameters such as the size and activity of the microbial community and soil enzymatic activities.

4.3.1. Microbial Activity

The soil microbial biomass (SMB) is commonly used to assess soil microbial activity, as this parameter responds quickly to changes in soil management. In this context, Zornoza et al. [274] stated that the quantitative description of the structure and diversity of the microbial community can be used as a tool for the evaluation of soil quality. That is, SMB can be used as an indicator of early changes in cropland management practices [275]. CA creates optimal conditions for microorganisms, with less frequent disturbance of the soil, increased SOM, improved water and thermal conditions, and increased diversity of substrates.

Crop diversification can increase soil microbial diversity and activities because the roots of cover crops release exudates in intercropping systems, contributing to greater microbial biomass [276]. In this context, Lopes and Fernandes [277] registered an increase in microbial biomass C with intercropping compared with monoculture. Singh et al. [278] reported that CA management systems can lead to an improvement in soil biota. Similarly, Wang et al. [279], in a study in drylands of northern China, reported a more diverse soil bacterial community in conservation tillage soils than in CT soils. Moreover, Silva et al. [280] registered a decrease in microbial diversity as tillage practices intensified. Dorr de Cuadros et al. [281] showed that microbial diversity was significantly higher in the NT system at four taxonomic levels (order, family, genus, and species) compared with the CT system. Henneron et al. [282] analyzed the long-term effects of CA on soil biodiversity, finding an improvement in the biomass and biodiversity of microorganisms. Baghel et al. [283], in a rice–wheat cropping system, recorded higher microbial biomass carbon under CA practices compared to CT. In a maize–mustard rotation, the zero-tilled flatbed and permanent bed CA practices improved soil biological properties, with higher SMB-C than CT [212].

Additionally, in a meta-analysis of 96 paired experiments, Li et al. [284] showed that CA practices (NT with residue retention) resulted in higher soil microbial biomass carbon (SMB-C) and nitrogen (SMB-N), and microbial quotient (qMic, Cmic-to-organic C ratio). In a continuous rice–wheat rotation, zero tillage and residue cycling compared to CT and residue removal increased SMB-C by 29 and 56%, respectively, whereas the SMB-N increased by 27 and 84%, respectively [285]. In a pigeon pea (*Cajanus cajan* (L.) Millsp.) and soybean intercropping system, conservation tillage systems recorded significantly higher SMB-C and SMB-N levels than CT without crop residues [286]. Spedding et al. [287] reported higher SMB-C and N levels in plots with residue retention than with residue removal, although the differences were significant only in the 0–10 cm layer. This agrees with Ceja-Navaro et al. [288], who found that in soils under NT with a monoculture of maize and removal of crop residue, microbial diversity was strongly reduced compared to soil under wheat NT where crop residues were retained. According to Legrand et al. [289], soil tillage is the agronomic practice that most influences soil bacterial diversity, with a greater functional and taxonomic diversity of bacteria in agricultural soils with minimal tillage compared to conventional tillage. In this context, Mathew et al. [290] reported a higher microbial biomass at the 0–5 cm depth in a long-term no-tillage system than in a conventional tillage system. According to Lopes and Fernandes [277], the changes in microbial community composition do not coincide with the increased soil physical quality resulting from CA practices, indicating the influence of other factors, such as edaphic or anthropic, on the soil microbial profile.

The crop system also influences microbial diversity. In this respect, Dorr de Cuadros et al. [281] reported greater microbial diversity in soils with a crop system based on cereals without legumes. That is, cereal straw substrates have a higher C:N ratio, which stimulates the microbial community to degrade organic substrate and leads to an increase in the microbial population.

4.3.2. Soil Enzymatic Activities

The microbial enzymatic activities of the soil serve as an indicator of the potential of the soil to decompose organic C and mineralize nutrients (P and N), and thereby nutrients available for plants. Soil enzymatic functions are greatly influenced by the cropping system and the degree of soil disturbance [291].

The main enzymes used to determine soil health are β-glucosidase, N-acetyl-glucosaminidase, and acid phosphatase, which are responsible for mediating C, N, and P cycling in the soil, respectively. According to Bonini-Pires et al. [292], the association of NT and increased crop rotation enhanced enzymatic activity in the soil surface. In a rice–wheat system in India, soil enzyme activities increased (5–18%) under an NT system with residues compared to an NT system without residues and a CT system without residues [293]. The implementation of CA in maize rotations improved soil enzymatic activities [104]. Similarly, Kumar and Babalad [286] registered significantly higher soil urease, dehydrogenase, and total phosphate activities in conservation tillage systems as compared to CT without crop residue. According to Choudhary et al. [285], soil enzyme activities were significantly increased in a conservation agriculture-based maize–wheat system.

In a study by Sharma et al. [294], an NT rice–wheat system with rice residue mulch increased soil dehydrogenase, cellulase, and alkaline phosphatase activities by 23%, 34%, and 14%, respectively, compared to CT. Pooniya et al. [212] reported that CA practices (zero-tilled flatbed and permanent bed) significantly increased dehydrogenase, alkaline phosphatase, and urease activities compared with CT.

The impact of CA practices on soil microbial and enzymatic activities in hillslope farming with rainfed olive orchards compared to CT is shown in Table 4 [259]. Moreover, Kandeler et al. [295] determined that protease and phosphatase activities significantly increased after only 2 years of minimum tillage compared to CT. Similarly, Roldán et al. [296] found that CA techniques based on zero tillage and legume cover remarkably enhanced the soil enzyme activities (dehydrogenase, urease, protease, β-glucosidase, and acid phosphatase). In a study by Pandey et al. [297], the no-till system fostered an improvement in the activities of β-glucosidase as well as microbial biomass carbon and nitrogen compared to CT. Similarly, Sinsabaugh et al. [298] found that minimum tillage promotes β-glucosidase activity due to the augmentation in microbial biomass, more substrate availability, and reduced soil disturbance, as was noted in a CA system compared to CT.

Table 4. Effect of CA practices on soil microbial and enzymatic activities in olive orchards throughout 3 year monitoring period (SE Spain).

Soil Management	Year	MB_N	MB_C	B-GLU	PRO	DHA	PHP
		(mg kg^{-1})		(µg pNP g^{-1} h^{-1})	(µg TRS g^{-1} h^{-1})	(µg TPF g^{-1} h^{-1})	(µg pNP g^{-1} h^{-1})
Minimum tillage and spontaneous vegetation strips	1st	5.8 (±2.2)	3.4 (±1.4)	401 (±1.2)	12.0 (±1.4)	99.20 (±1.9)	131.5 (±11.8)
	3rd	6.9 (±3.4)	3.8 (±1.1)	452 (±2.4)	12.8 (±1.5)	111.8 (±3.4)	139.8 (±22.4)
Minimum tillage and legume strips	1st	5.0 (±1.2)	3.1 (±1.0)	461 (1.9)	11.9 (±0.9)	100.7 (±2.7)	120.4 (±17.1)
	3rd	6.4 (±0.9)	4.2 (±2.4)	483 (±3.5)	12.7 (±1.6)	119.1 (±5.2)	131.4 (±13.7)
Conventional tillage	1st	5.3 (±0.8)	2.0 (±0.8)	131 (±1.2)	11.7 (±1.4)	92.43 (±5.1)	122.0 (±21.5)
	3rd	4.3 (±0.7)	1.3 (±0.9)	196 (±1.8)	12.4 (±1.9)	92.78 (±4.9)	129.6 (±20.9)

β-GLU, β-glucosidase; PRO, protease; DHA, Dehydrogenase; PHP, Phosphatase; MBN, microbial biomass-nitrogen; MBC, microbial biomass-carbon. Values in parentheses are standard deviation.

Ultimately, it is evident that CA practices positively impact soil microorganisms and microbial processes ascribed to changes in the quantity and quality of plant residues that enter the soil, their spatial distribution, changes in the provision of nutrients, and physical alterations. Consequently, the alternative modifications to CT systems, especially those based on methods used in CA, are able to boost important functions for soil health restoration.

4.3.3. Earthworms

Earthworms are one of the most important soil macrofaunal groups and are described as ecosystem engineers because of their effects on soil properties and on the availability of resources for other organisms [299]. They determine the nutrient cycle, microbial activity, the stability of soil aggregates, and the density and distribution of other invertebrates. Soil tillage causes physical damage to earthworms as well as alterations of their habitat, and can vary the community structure and relative abundance of earthworms [300]. The variability in burrowing and feeding behaviors influences the effects that tillage type can have on earthworms [301]. Thus, the species that inhabit the topsoil are most at risk of being adversely affected by plowing [302]. Earthworms have been observed to respond positively to CA practices. Contrarily, a study by Baldivieso-Freitas et al. [303] did not register any positive effects of the combination of CA techniques (reduced tillage by chiseling and green manures) on earthworm populations in a Mediterranean environment. However, organic fertilization showed a more significant role and enhanced their population. Therefore, it is crucial to understand how different factors (soil properties, crop rotations, and climate conditions) interact when designing a sustainable organic system.

According to Van Capelle et al. [304], the increase in earthworm density under no-till systems is due to the interactions of different effects: reduced injuries, decreased exposure to predators at the soil surface, reduced microclimate changes, and increased availability of organic matter. Radford et al. [305] reported that earthworm numbers increased fourfold with a zero-tillage system as compared to CT. Birkás et al. [306], in a study in Hungary, registered significantly more earthworms in soils under a conservation tillage system that included leaving stubble residues on the surface, compared to soils that were deteriorated by tillage pans and left bare without residues. In a study in Zambia, soils under CA practices with residue retention and crop rotation had higher earthworm populations in the top 30 cm than soils under conventionally ploughed practices [87]. Errouissi et al. [307] showed that zero tillage with surface residue increased the populations and diversity of soil invertebrates, including earthworms, compared to CT because of improved soil properties and a lack of soil disturbance. Crop residues retained on the soil surface and minimum soil disturbance improve soil structure, are a food resource, and cool the soil temperature, allowing the number and biomass of earthworms to increase [308]. In a study in central Mexico, Castellanos-Navarrete et al. [84] showed that CA produced an evident increase in the abundance and biomass of earthworms compared to CT. Sharma and Dhaliwal [309], in a study of rice–wheat cropping systems in South Asia, concluded that a zero-tillage system with crop residue retention improved micronutrient contents and provided feeding for soil macrofauna, especially earthworms, as compared to conventional tillage without residue. In a long-term trial in Zambia, Muoni et al. [310] concluded that reduced tillage systems and crop rotations increase biological activity, with the density of termites and earthworms being higher in CA systems than in CT systems. Henneron et al. [282] reported an increase in anecic earthworms in the long term in CA systems. Additionally, Pelosi et al. [302] reported that the decrease in soil tillage intensity led to an increase in functional diversity and an increase in the density of anecic earthworms. Several studies have reported a positive impact of management systems that include diversified crop rotations on earthworm density [311,312].

4.3.4. Soil Respiration

Soil respiration comprises the oxidation of organic matter by microorganisms and rhizosphere respiration [313]. It is a measure of the metabolic activity of the soil microbial community and is considered as the second-largest terrestrial carbon flux worldwide [314]. It is one of the most widely used soil biological indicators in soil quality evaluations [62].

Soil respiration is sensitive to soil disturbances, so it can be used as an indicator to detect soil degradation early [315].

Soil management affects the soil microclimate and biotic factors (soil organic carbon, aboveground biomass, root biomass, and plant residues) that indirectly influence soil respiration [316]. Several studies have reported the effect of conservation agriculture practices on soil microbial respiration [277,317,318], without consistent trends. Some studies did not report significant differences in soil respiration between conventional tillage and conservation agriculture practices [277,319,320]. This may be because tillage seems to affect the temporal distribution more than the total amount of CO_2 emissions from the soil [321]. Therefore, to achieve an accurate assessment of the effects of agricultural practices on soil respiration, it is necessary to design a seasonal sampling [322]. In contrast, other studies recorded significantly higher soil respiration values in CA systems than in CT systems. In a study in Cambodia, Edralin et al. [317] reported higher soil respiration in CA (55.9 $\pm$ 4.8 kg CO_2-C ha^{-1} day^{-1}) than in CT (36.2 $\pm$ 13.5 kg CO_2-C ha^{-1} day^{-1}). In the long term, NT increased soil respiration compared to CT, by 16, 19 and 26% after 6, 20 and 35 years of implantation [103]. Additionally, a 12 year study showed that, compared to conventional tillage, no-till practices resulted in higher soil microbial respiration [323]. Sapkota et al. [103] reported higher soil respiration in no-tillage systems than in conventional tillage (+44%). In an apricot orchard, cover crops increased soil respiration compared to plots with bare control, herbicide control or mechanical cultivation [324].

According to Williams et al. [325], agricultural practices that imply the greater crop diversity, reduction in mechanical soil disturbance and/or an increase in organic amendment inputs that characterize CA systems improve the microbiological activity of the soil. CA practices increase organic carbon inputs to the soil, for example, through plant residues, improving soil biological activity [326]. In this context, Bera et al. [327] observed a significant and high positive correlation between SOC and basal soil respiration, of 0.84.

5. Conclusions and Future Perspectives

The main challenge of conserving and improving soil health is guaranteeing its long-term productivity and environmental sustainability. As was reviewed, CA systems can be implemented to minimize negative socioeconomic and environmental consequences associated with soil degradation by enhancing soil health and promoting the sustainability and multifunctionality of agroecosystems.

To meet the global challenges of food security and environmental conservation, CA has been identified as one of the technological options for a sustainable intensification of agriculture. CA systems have clear advantages over conventional agricultural systems in improving soil health and the efficient use of natural resources, reducing the environmental impacts of agricultural activities, saving inputs, reducing the cost of production, etc.

Regarding the implementation of CA practices, there are a number of restrictions and challenges that must be addressed in order to increase their adoption on a large scale:

- Unavailability of appropriate equipment and machines, especially for small- and medium-scale farms;
- Use of crop residues for livestock feed and fuel;
- Lack of knowledge about the benefits of CA and how to implement CA;
- Farmer mind-sets that limit the adoption of CA due to traditions or prejudices;
- Lack of technical and financial support from governments, international organizations, and/or extension agencies;
- Technical problems that can arise with the adoption of CA practices such as inadequate weed management, nutrient stratification, lower N availability, development of surface crust, etc., which can translate into a decrease in yield and can motivate farmers to abandon the system.

To overcome these constraints and increase the performance of CA worldwide, it is essential that CA systems be well-adapted to specific agronomic, environmental, social, and economic conditions. Consequently, it is necessary to carry out the following measures, among others:

- Improve the availability of machinery and supplies of plant nutrition;
- Identify and eliminate sociocultural barriers to CA adoption;
- Improve locally adapted management, such as appropriate crop rotations or the frequency and optimal timing of strategic tillage;
- Increase institutional support, research, efficiency of extension services, and information dissemination mechanisms.

Finally, in order to guarantee the long-term productivity and environmental sustainability of agroecosystems, it will be vital to develop new tools and methodologies to assess soil quality and health that can be used to evaluate and guide soil management decisions.

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